Sun-climate connection

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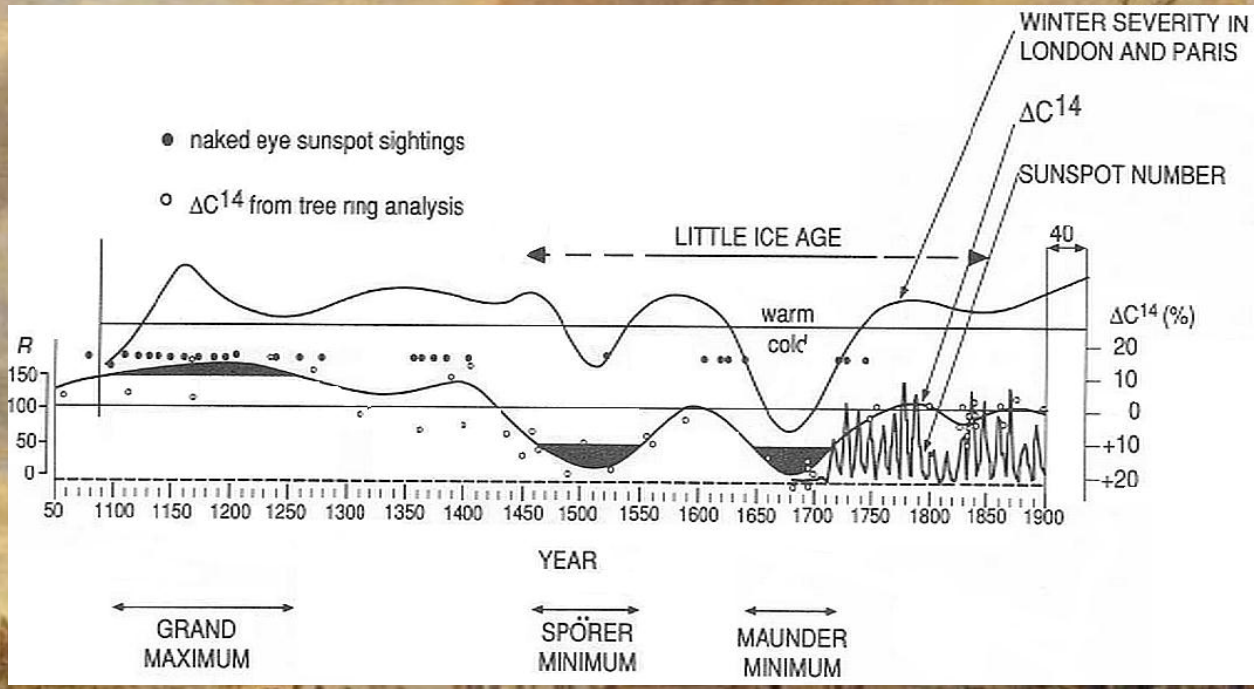
Sir William Herschel (MNRAS, 1801)

Short-term solar climate connections

Times of many sunspots "may lead us to expect a copious emission of heat and therefore mild seasons," and periods of few spots would signal "spare emission of heat" and "severe seasons" which would raise the price of wheat.

Jack Eddy (Science, 1976)

Long-term solar-climate connections



Maunder and other grand minima: prolonged periods of no or very few sunspots

Grand minima coincide with little ice ages

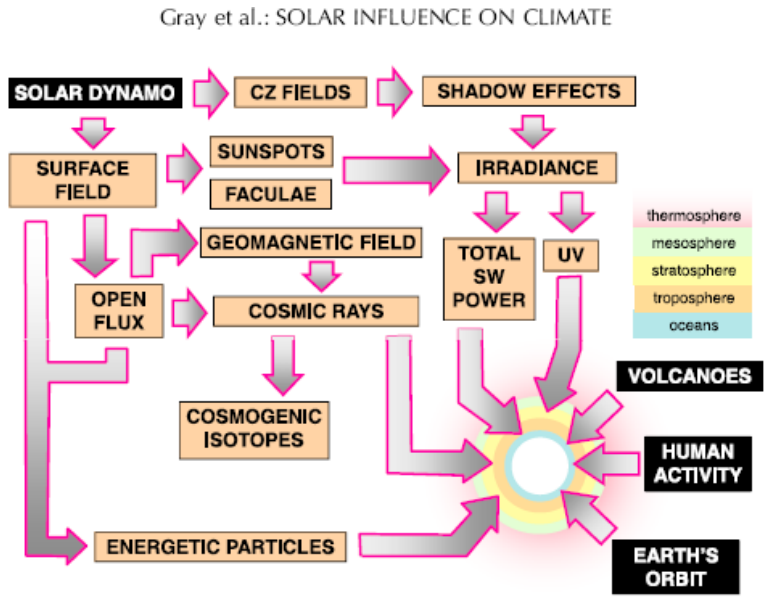
View of River in Winter (1660) by Aert can der Neer (1603-1677)

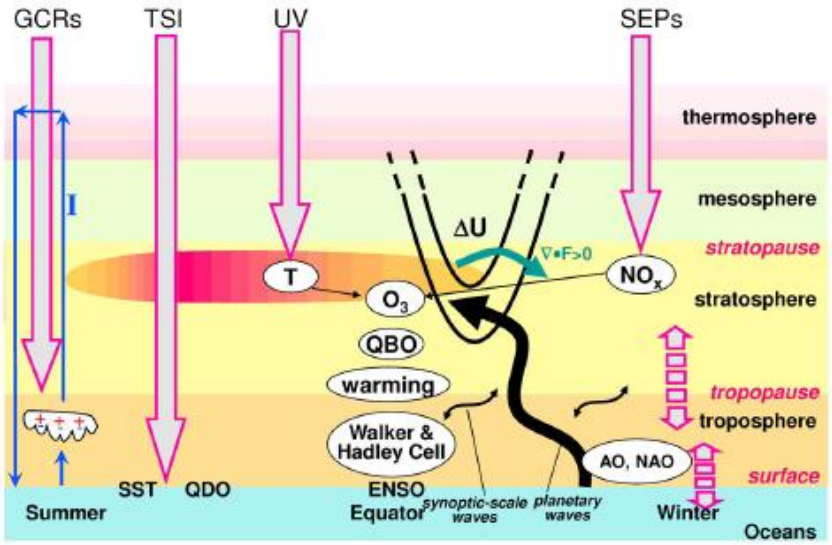
Why study sun-climate connection?

For at least two reasons:

scientific and practical

1. Scientific - because it is interesting





We need to understand:

how the Sun works;

how the Earth's system works;

and the whole chain of processes from the Sun to the Earth

2. Practical – because it is important for our everyday life

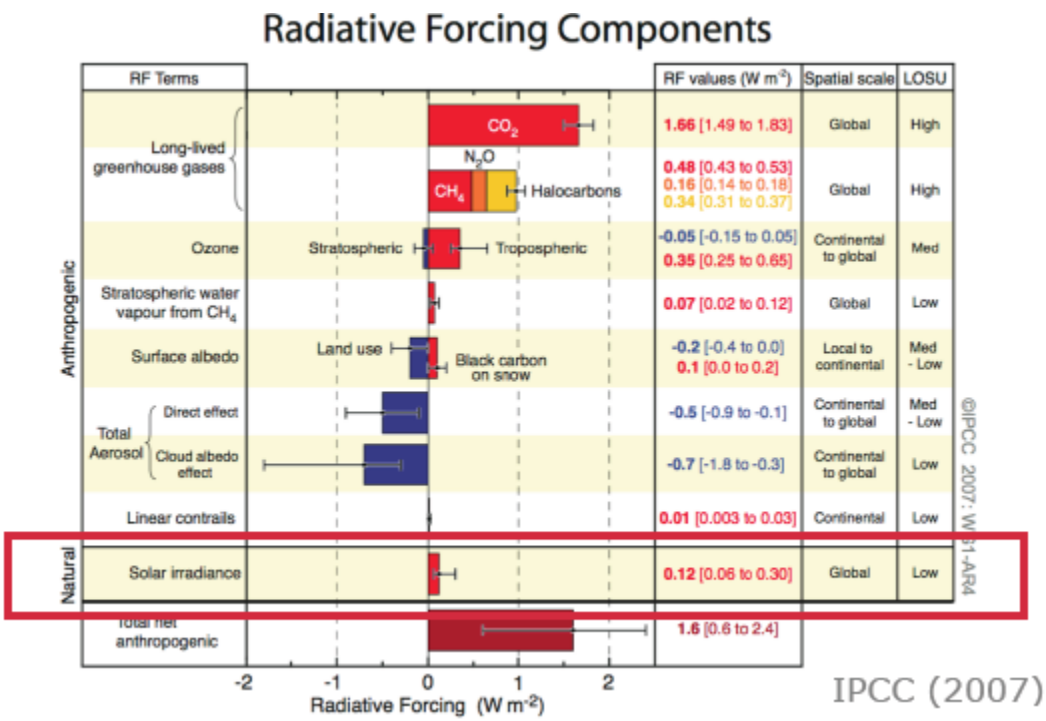
ipcc
INTERGOVERNMENTAL PANEL ON climate change

Climate Change Assessment Report 4 (2007)
Summary for Policymakers

-"warming of the climate system is ***unequivocal***";

- "most of the observed increase in global average temperatures since the mid-20th century is ***very likely*** due to the observed increase in anthropogenic greenhouse gas concentrations."

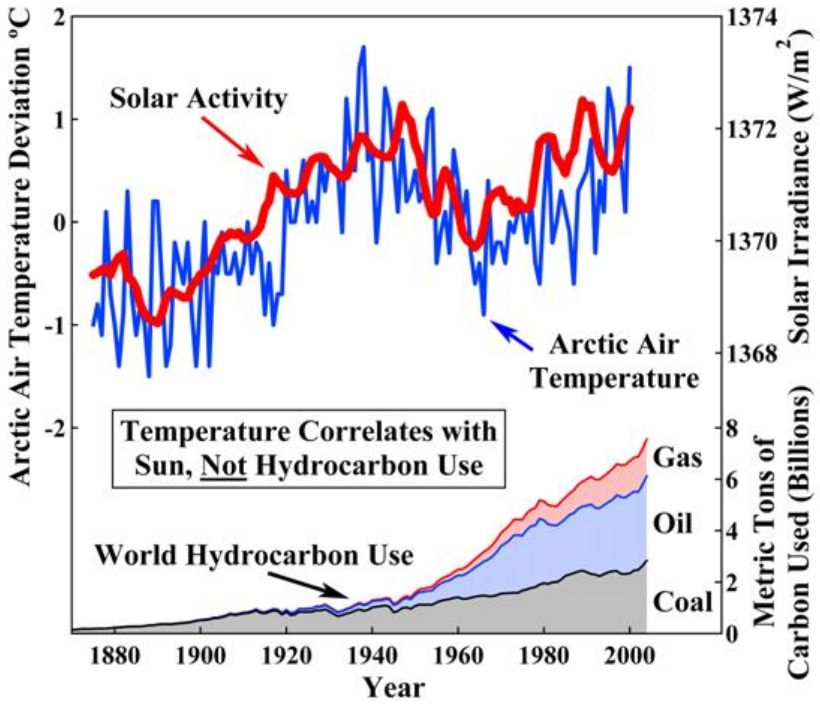
Likely >66% probability
Very likely >90% proibability

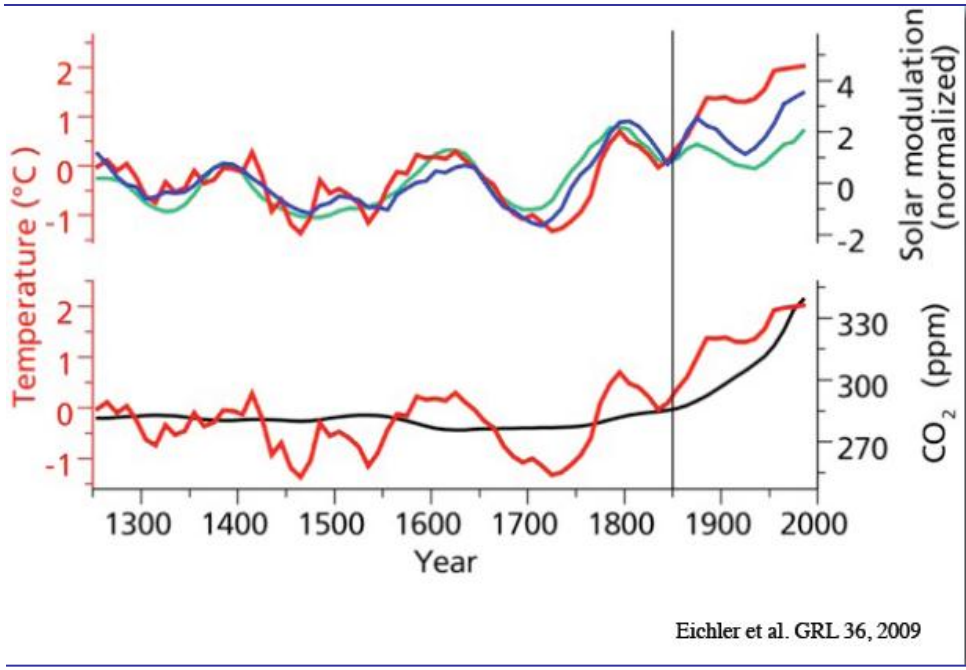


IPCC (2007)

IPCC: "Only a minor contribution from solar activity"

Controversy about the relative impact of solar and human induced climate change

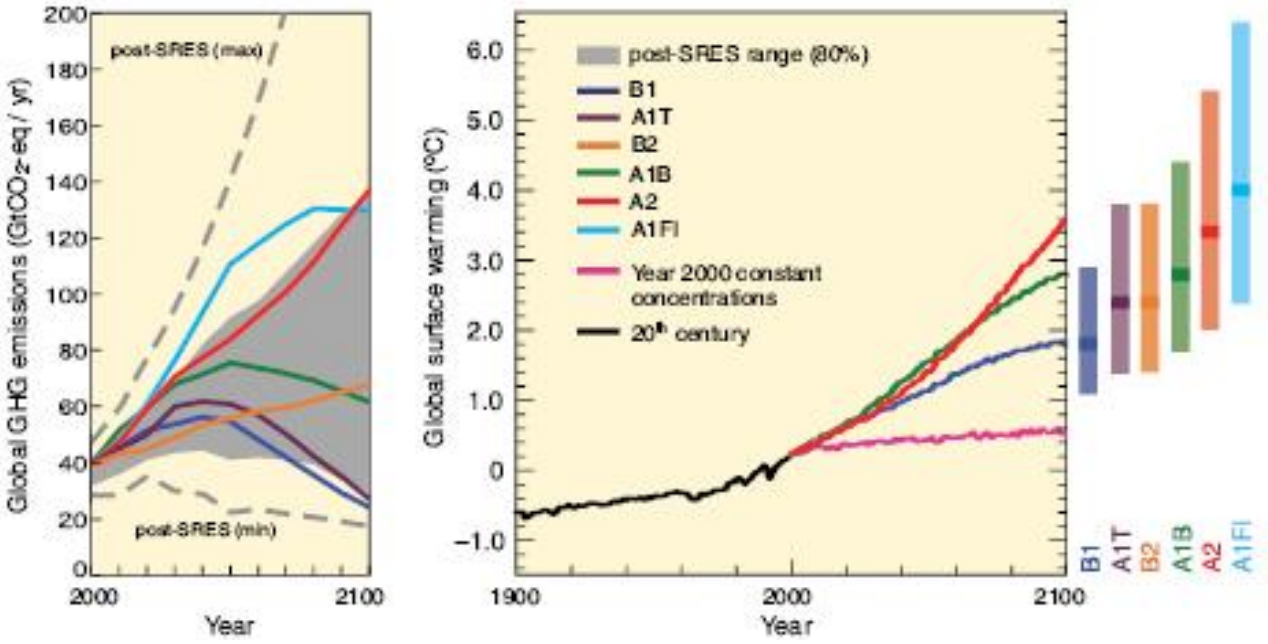




Temperature correlates with solar activity, not with CO_2

"Low level of scientific understanding of the solar influence" (IPCC, IV AR)

Scenarios for GHG emissions from 2000 to 2100 (in the absence of additional climate policies) and projections of surface temperatures



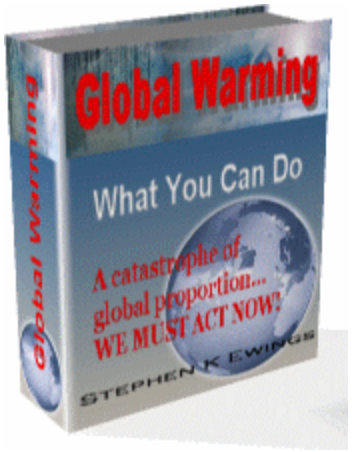
"Unmitigated climate change would, in the long term, be *likely* to exceed the capacity of natural, managed and human systems to adapt"

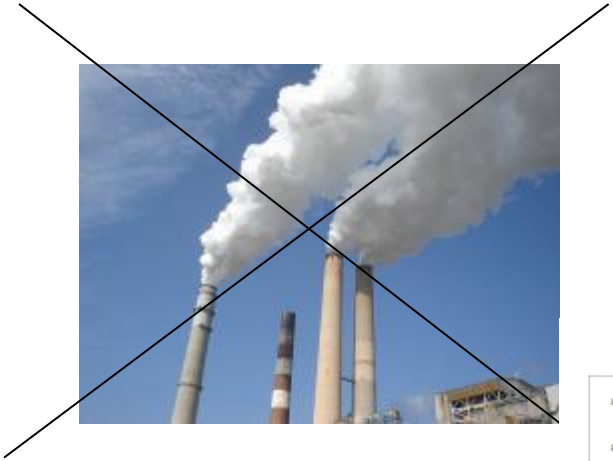
Measures to mitigate climate change:

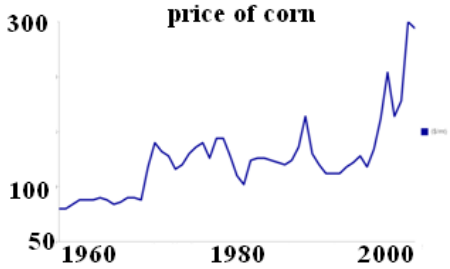
Reduction of emissions ⇒ retarded economical growth

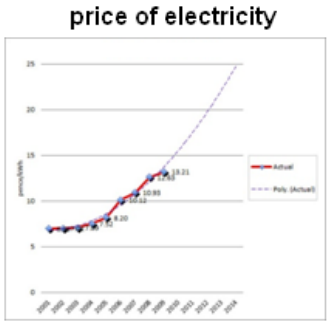
Renewable energy sources ⇒ increased cost of energy

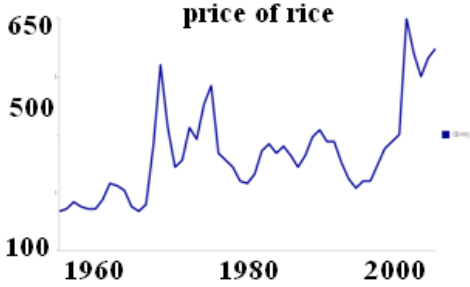
Biofuels ⇒ increased cost of food





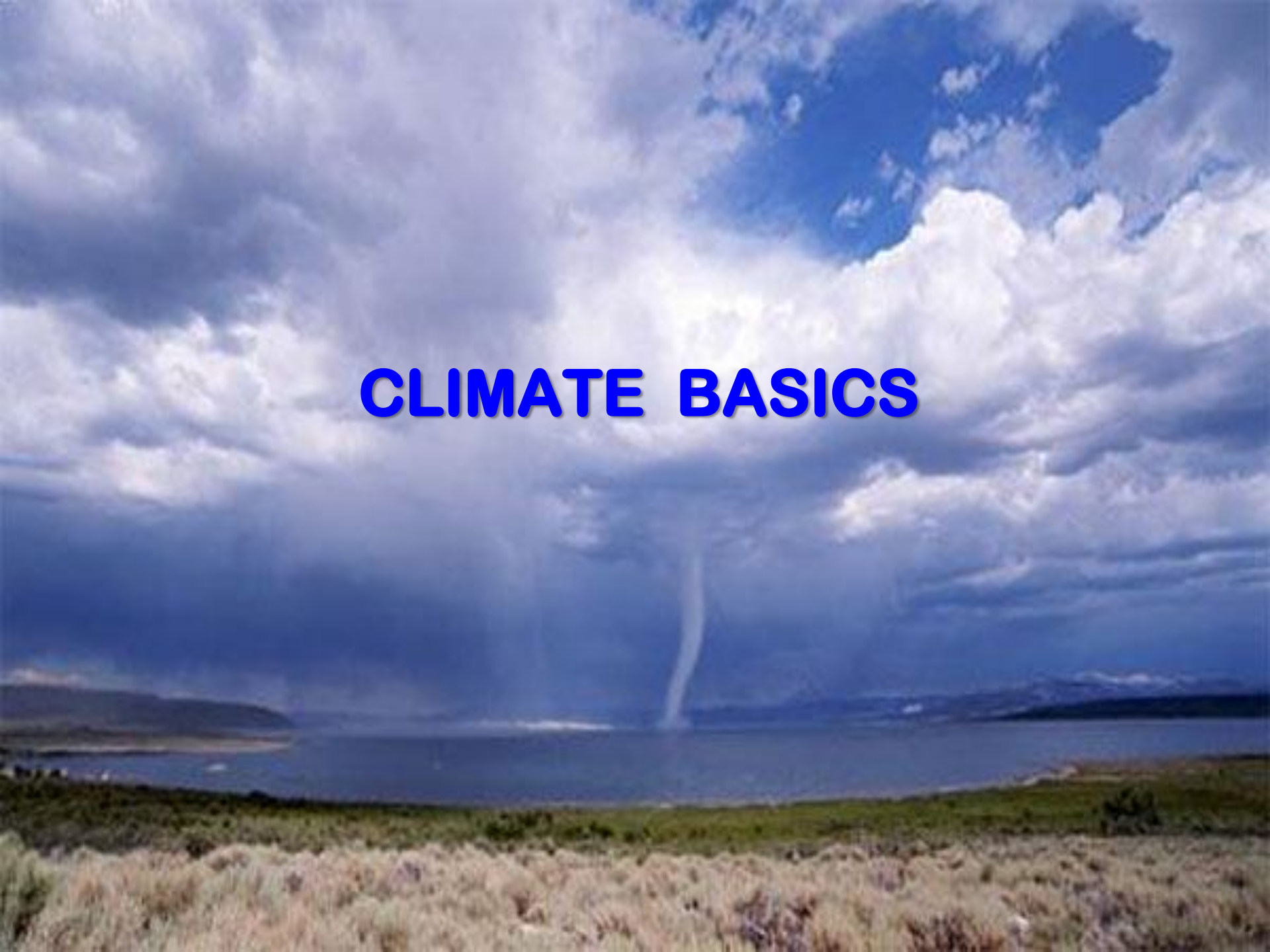






Must we try to mitigate climate changes…

…or shall we just adapt to them?


CLIMATE BASICS

Differences between weather and climate

Weather	Climate
It is an instantaneous atmospheric condition.	It is an average atmospheric condition.
It can change rapidly, within even less than an hour.	It sustains over a period of 30 years, as defined by World Meteorological Organization (WMO).
It prevails over a small area.	It prevails over a large region.
It has only limited predictability.	It is almost constant.
It depends primarily on density, temperature and moisture differences between one place and another.	It depends on latitude, distance to the sea, vegetation, presence or absence of mountains, and other geographical factors.

"Climate is what you expect, weather is what you get"

climate system

5 “spheres”

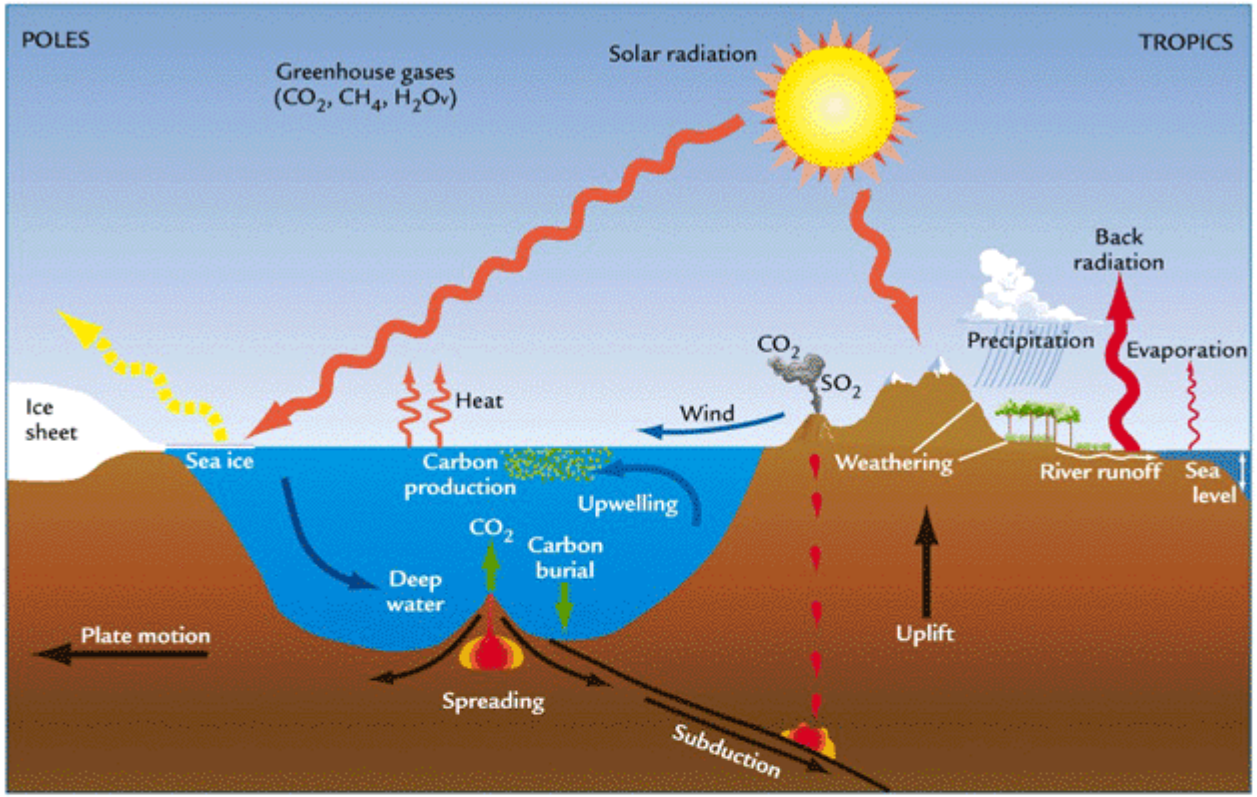
atmosphere

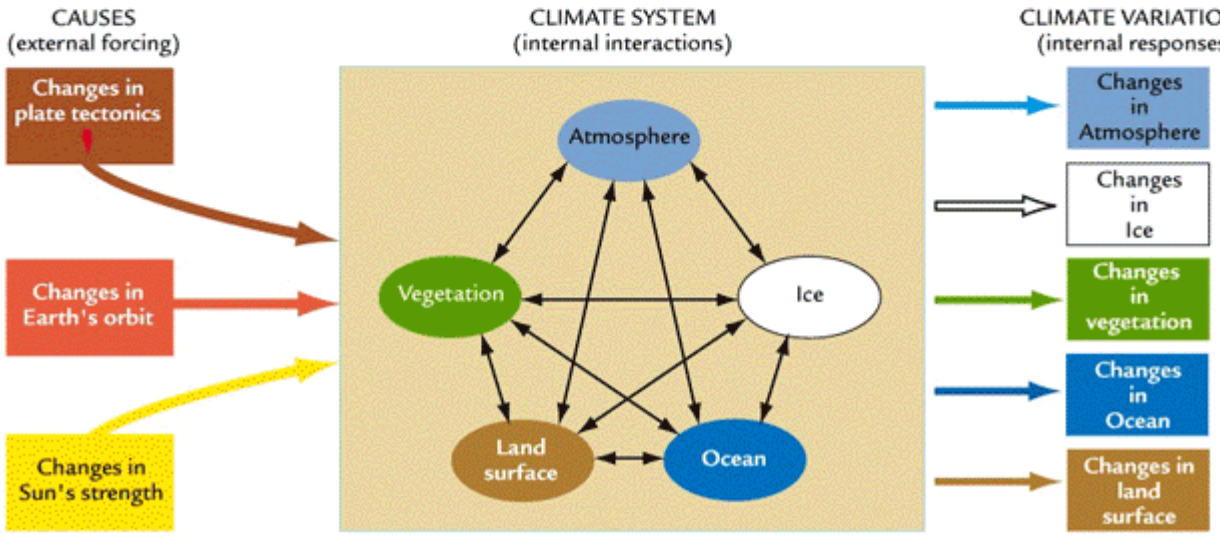
hydrosphere

criosphere

lithosphere

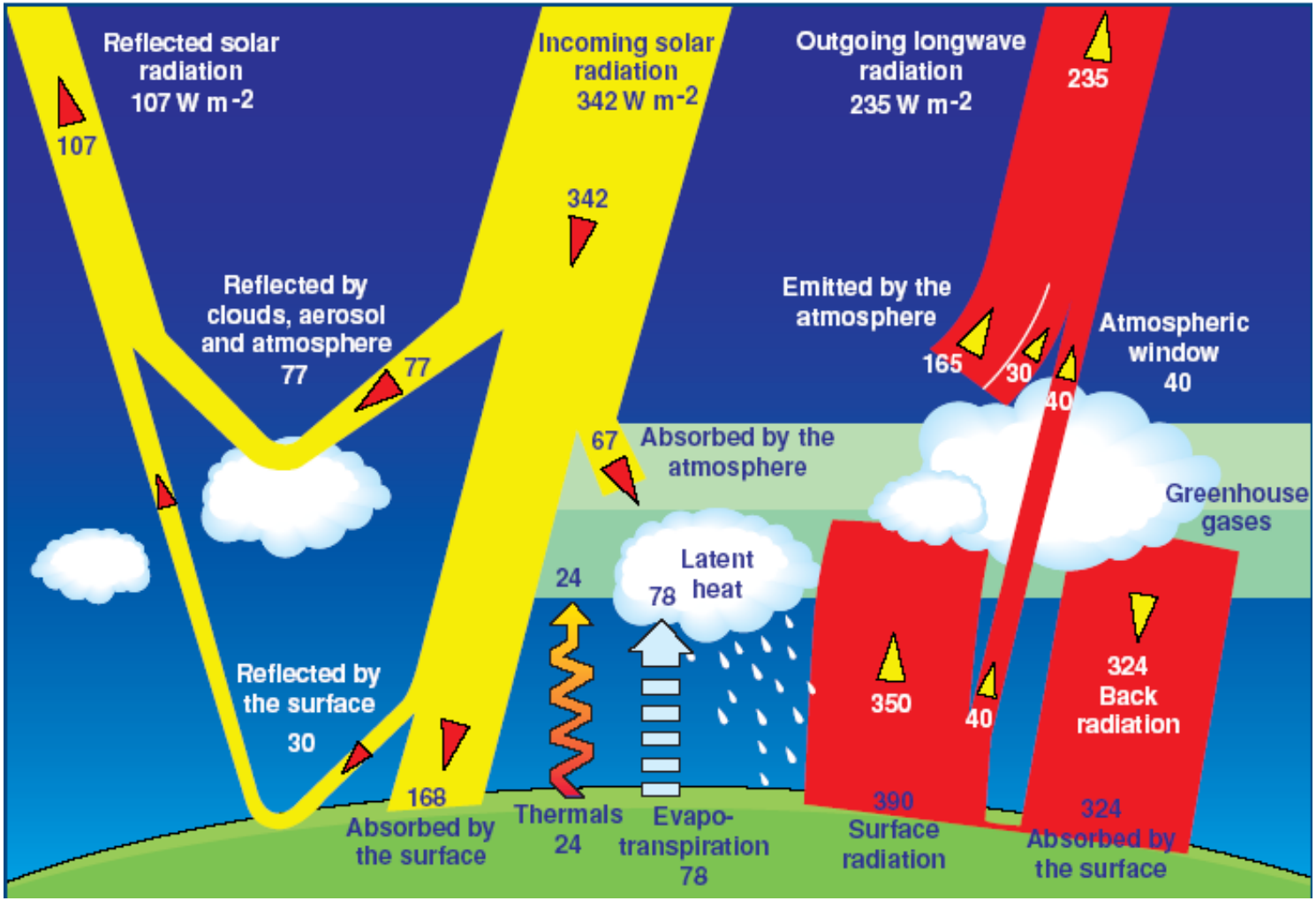
biosphere



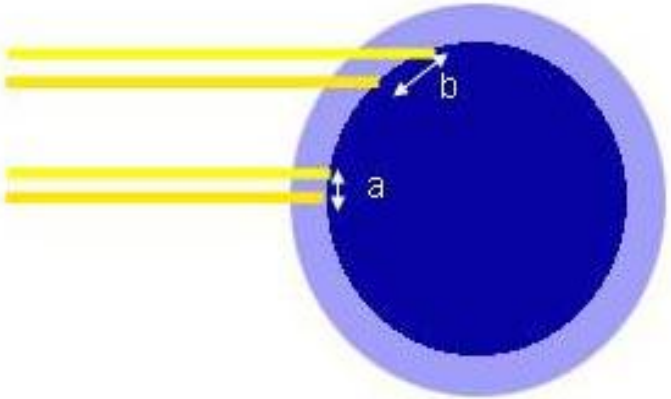


Ruddiman (2001)

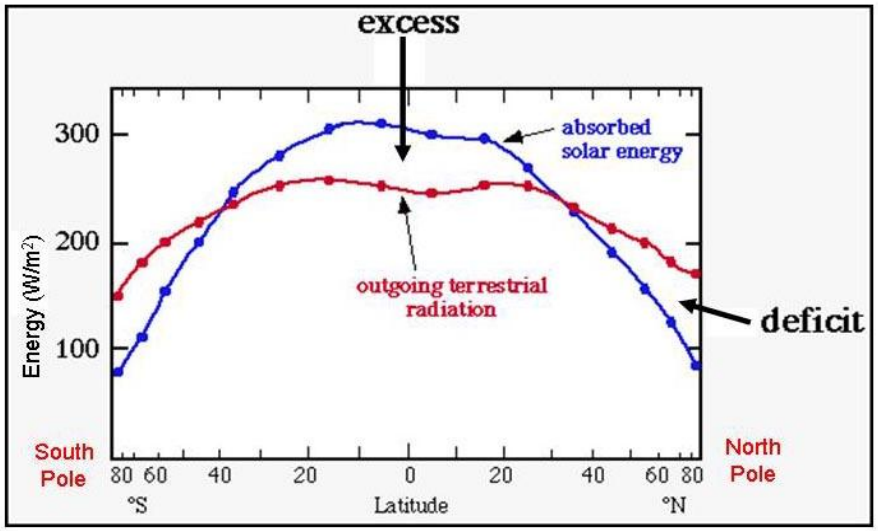
Earth radiation budget



Latitudinal distribution of radiation



- The Earth gets more energy per unit area in the tropics than at higher latitudes



- Latitudinal distribution of incoming solar (shortwave) and outgoing (longwave) terrestrial radiation

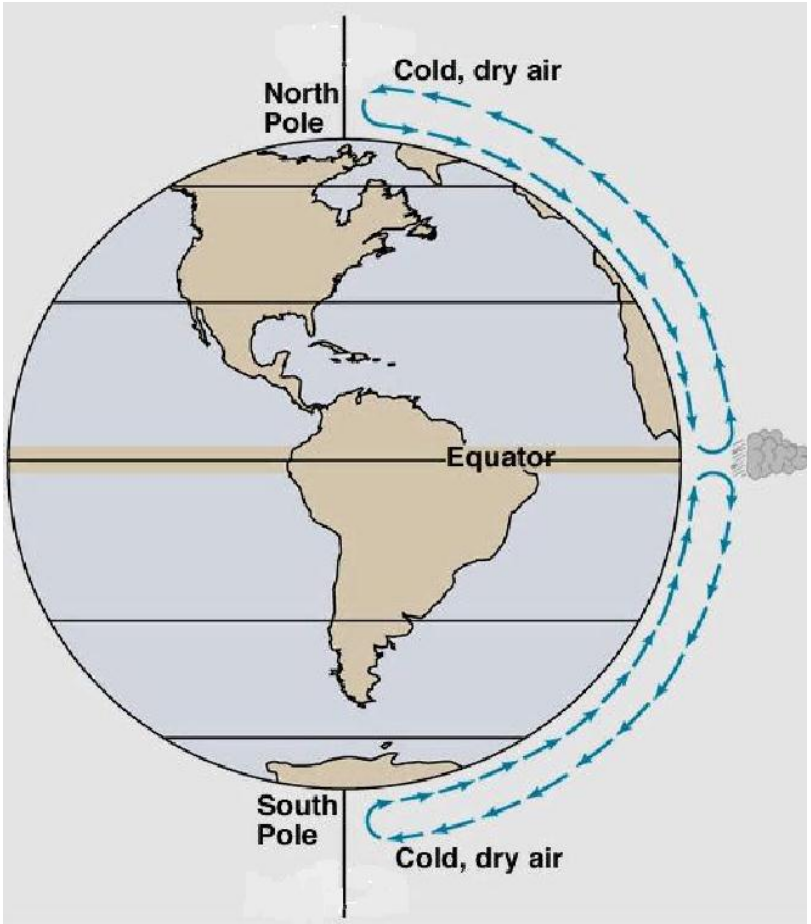
Atmospheric circulation – the system of the large-scale atmospheric motions over the Earth

due to the differential heating of the Earth's surface

If the Earth didn't rotate:

- heated air at the equator rises to the top of the troposphere
- proceeds south and north toward the poles
- descend there
- returns to the equator.

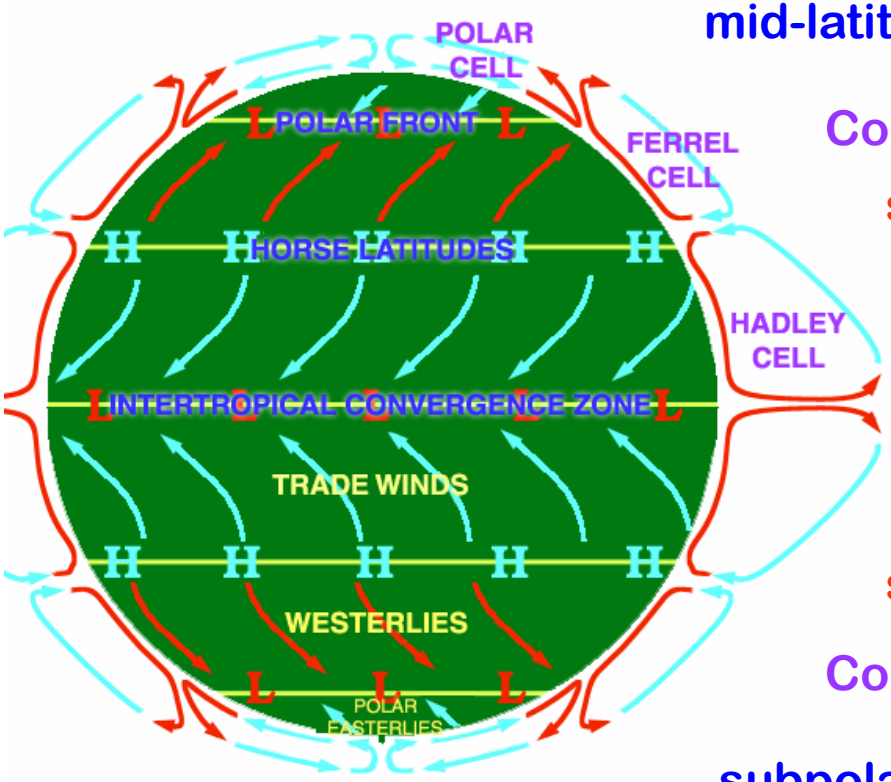
=> **2-cell circulation (one in each hemisphere)**



But the Earth does rotate:

Tropospheric
polar vortex

subpolar lows
mid-latitude cyclones



Coriolis force

subtropical high, jet stream, waves

Coriolis force

0° equatorial low

Coriolis force

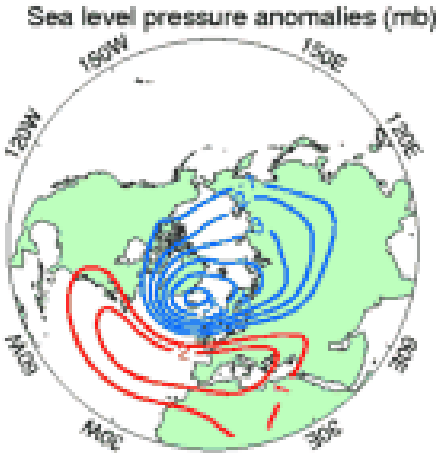
subtropical high, jet stream, waves

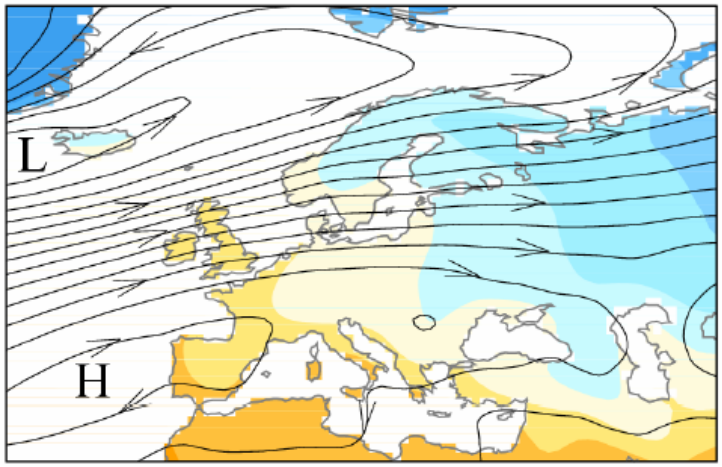
Coriolis force

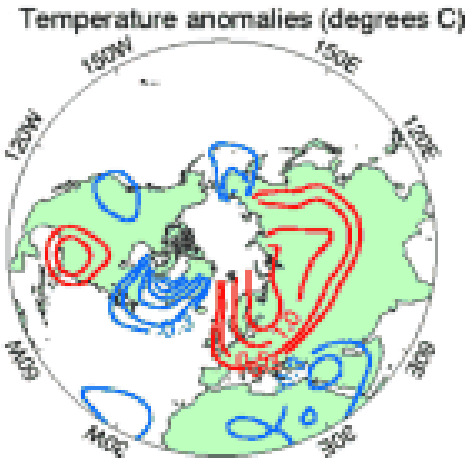
subpolar lows
mid-latitude cyclones

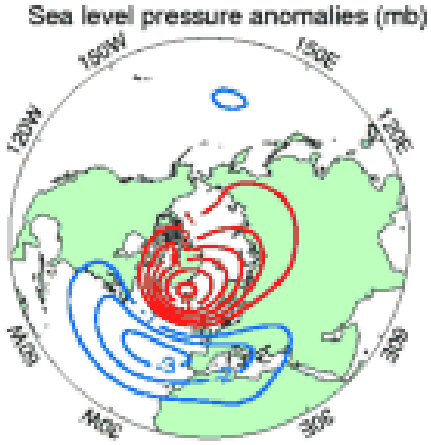
Tropospheric
polar vortex

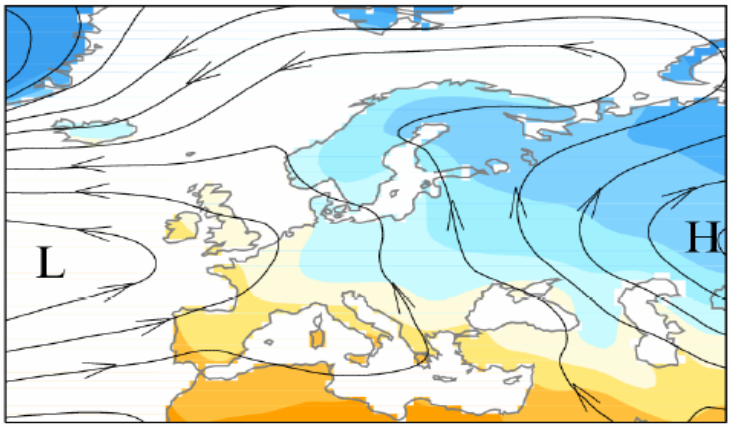
North Atlantic Oscillation (NAO) – sea-saw variation between atmospheric centers of action in middle and high northern latitudes determining the large-scale atmospheric circulation and temperature over most of NH

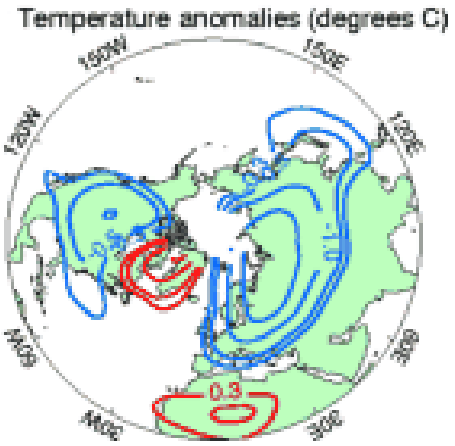




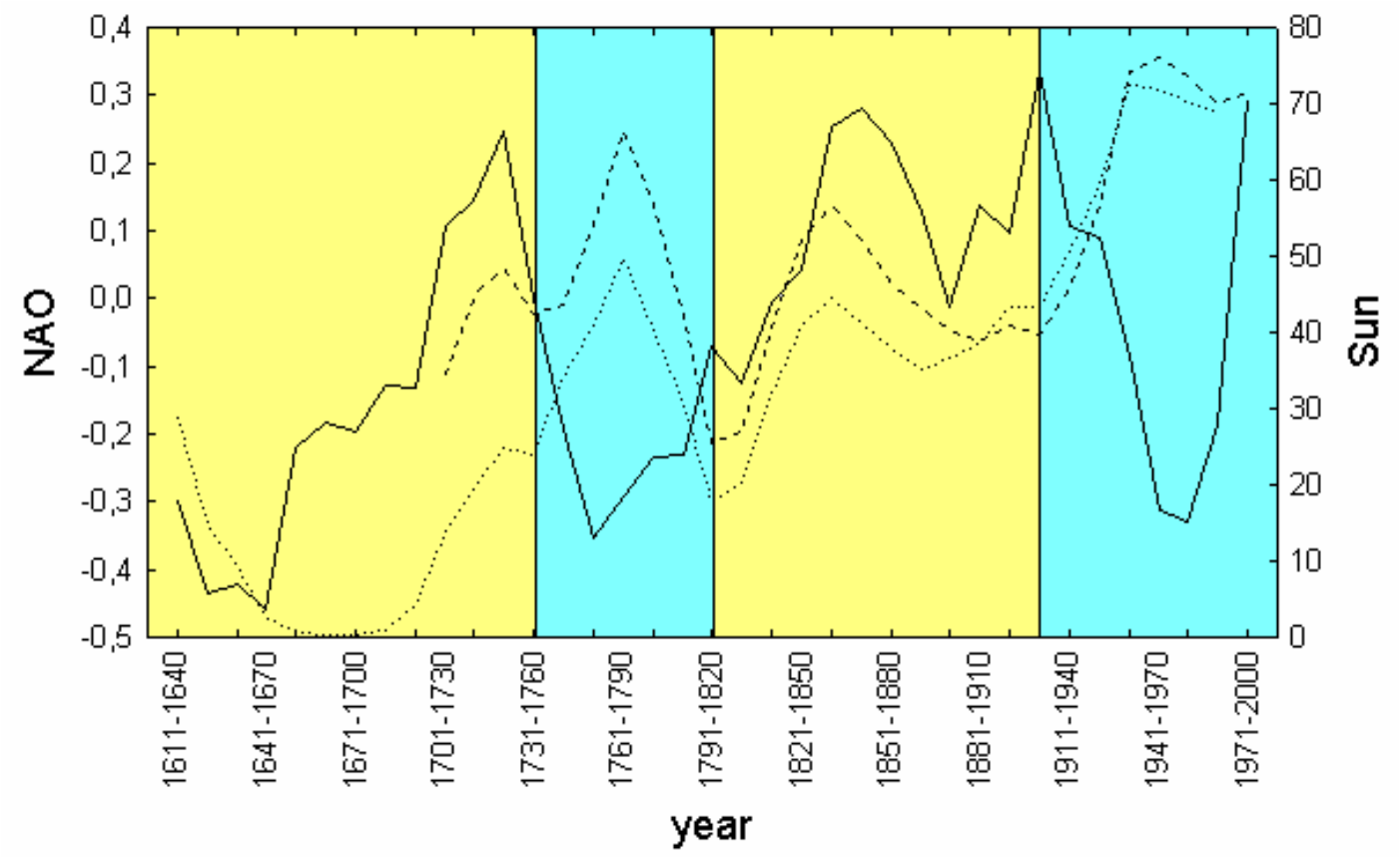






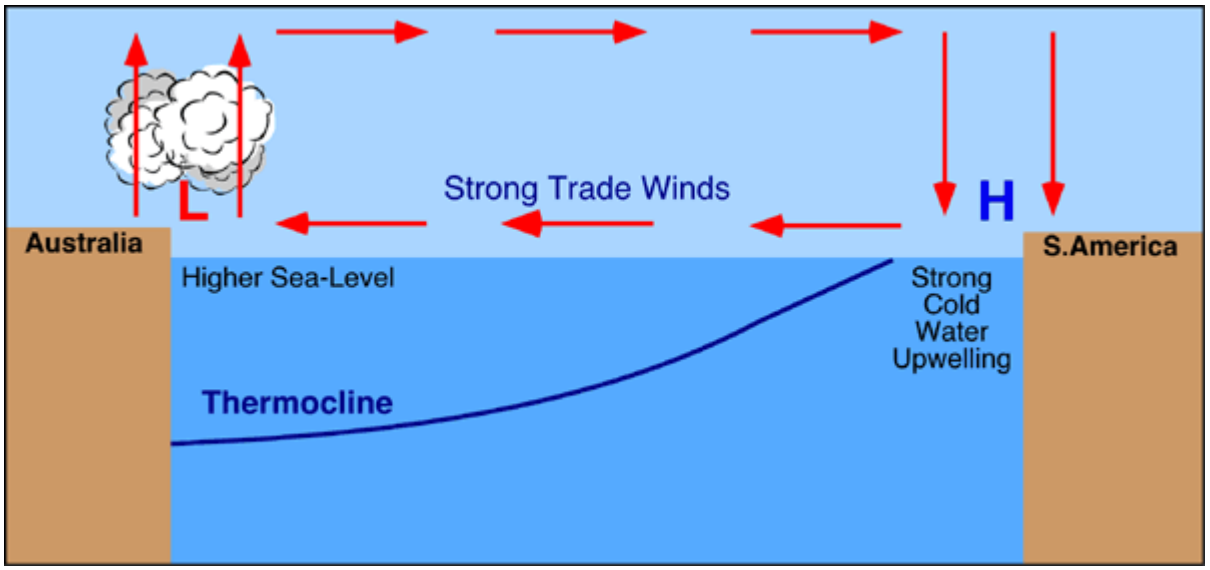


NAO and sunspot number

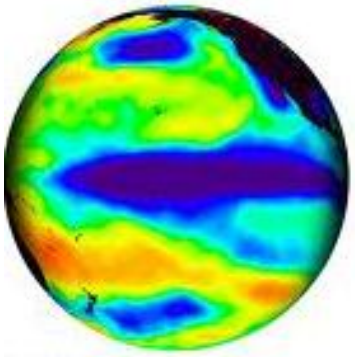


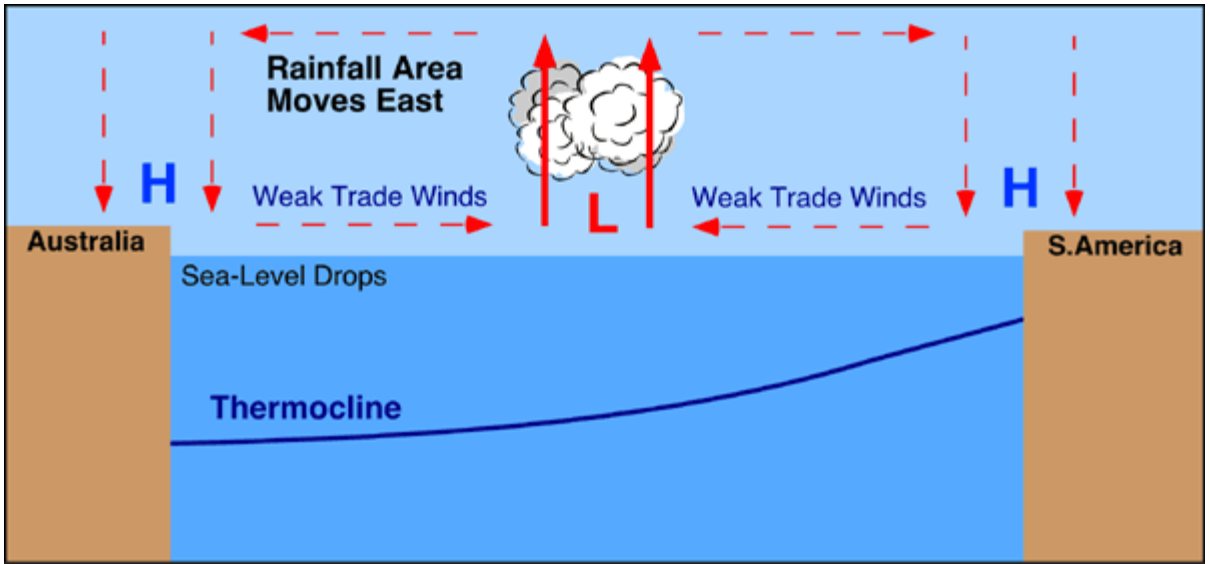
Correlated with solar activity: positive and negative correlation in consecutive secular solar cycles

El Niño/Southern Oscillation

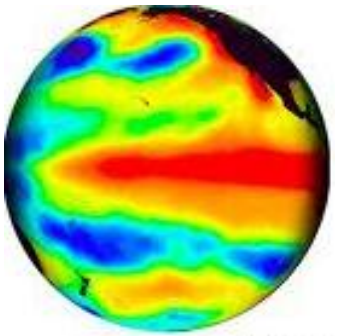


Normal/La Niña

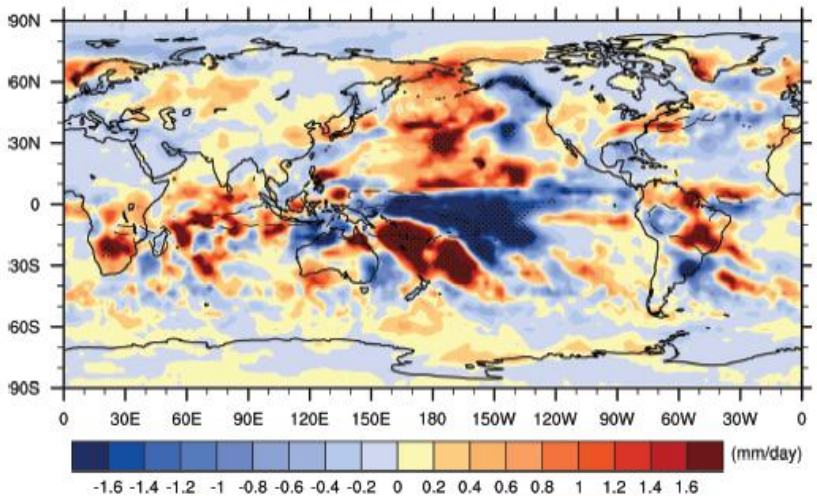




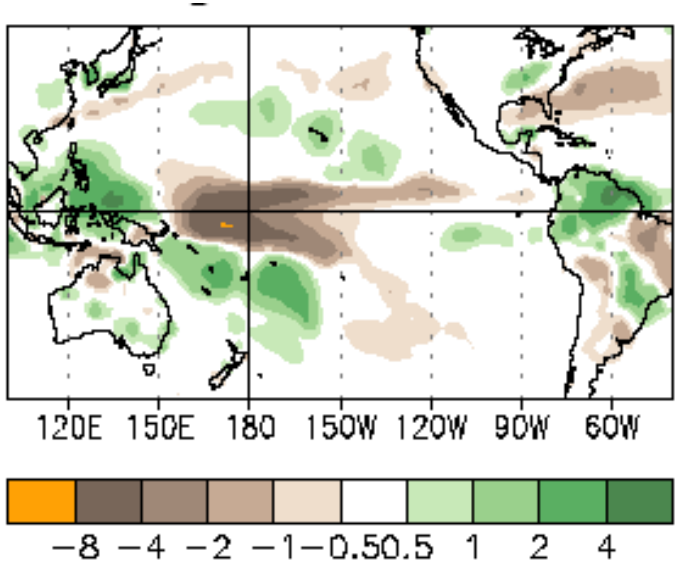
El Niño



Solar activity and El Niño

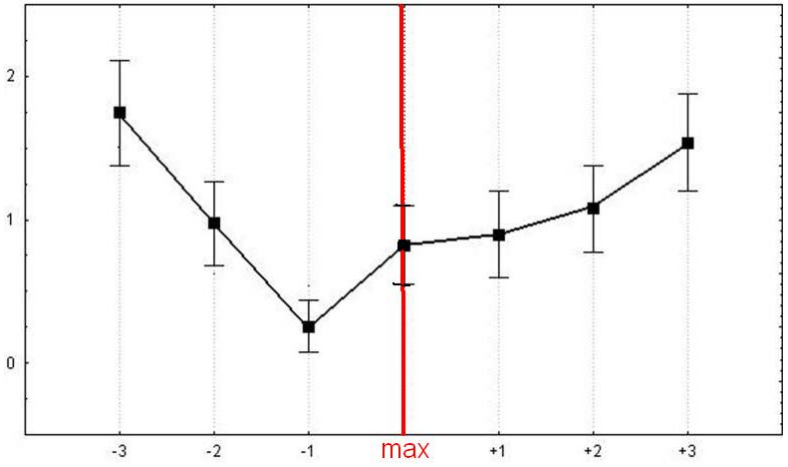


a typical La Niña year

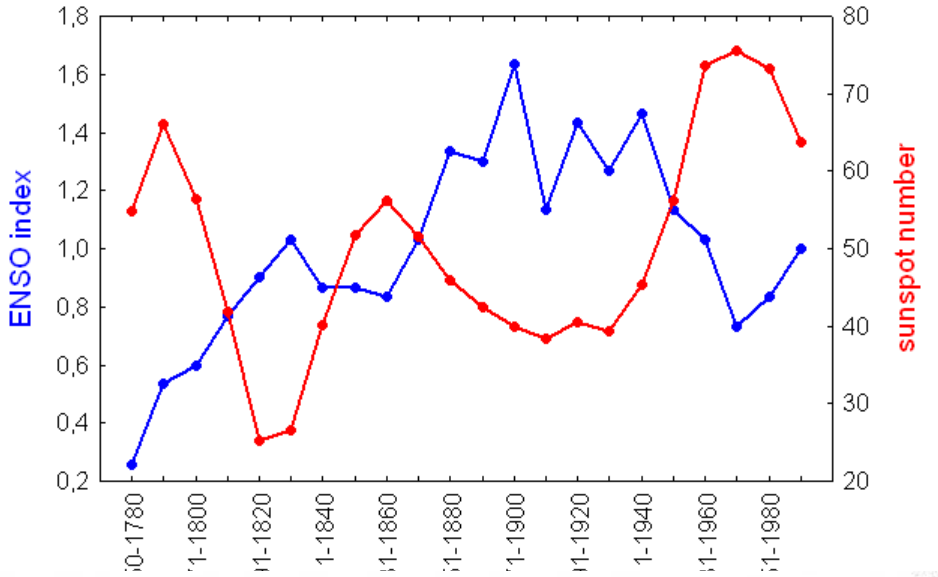


high solar activity years

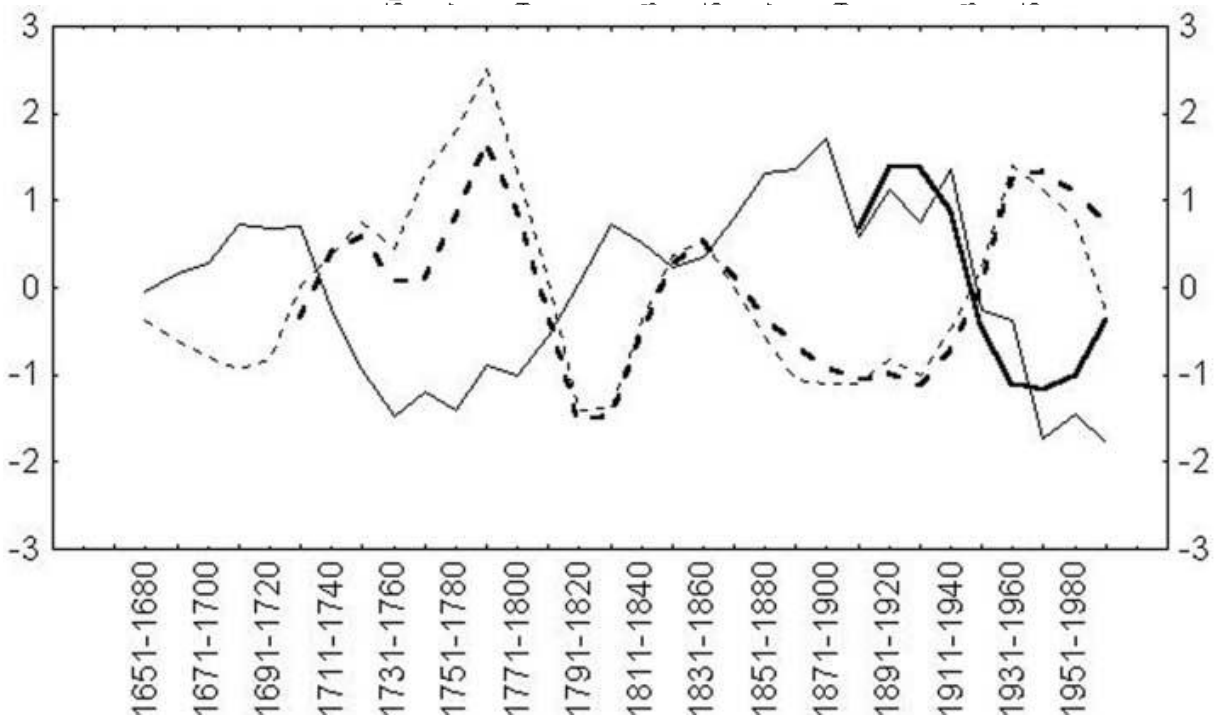
La Niña type conditions prevail during high solar activity years



Long-term vaviations of solar activity and El Niño



El Niño frequency and intensity decrease with increasing solar activity both on centennial time-scales



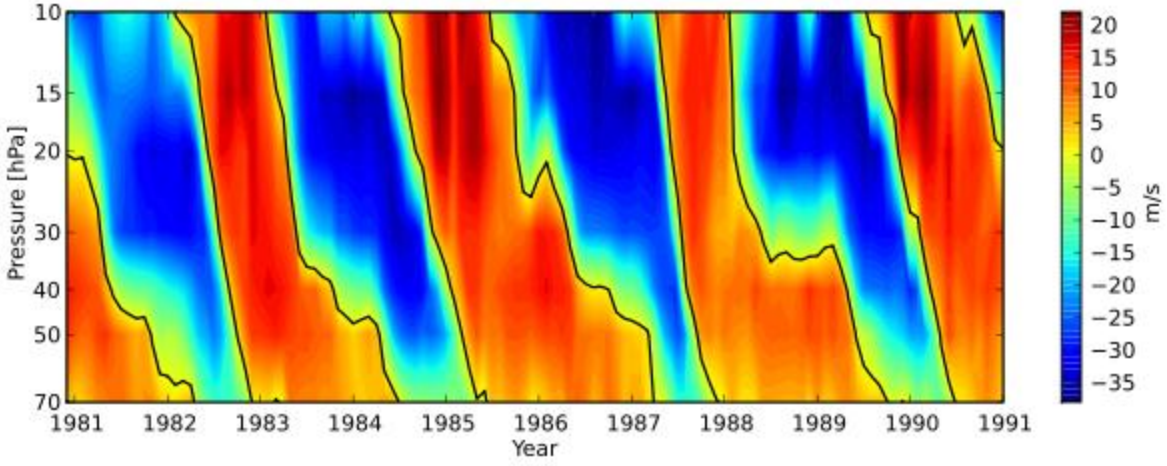
Quasibiennial oscillations

Krakatau eruption (1883): the dust circled the Earth in 13 days from east to west

⇒ "Krakatau Easterlies"

In 1908 Berson launched observational balloons above Lake Victoria in Africa and at 15 km they were carried from west to east

⇒ "Berson Westerlies"

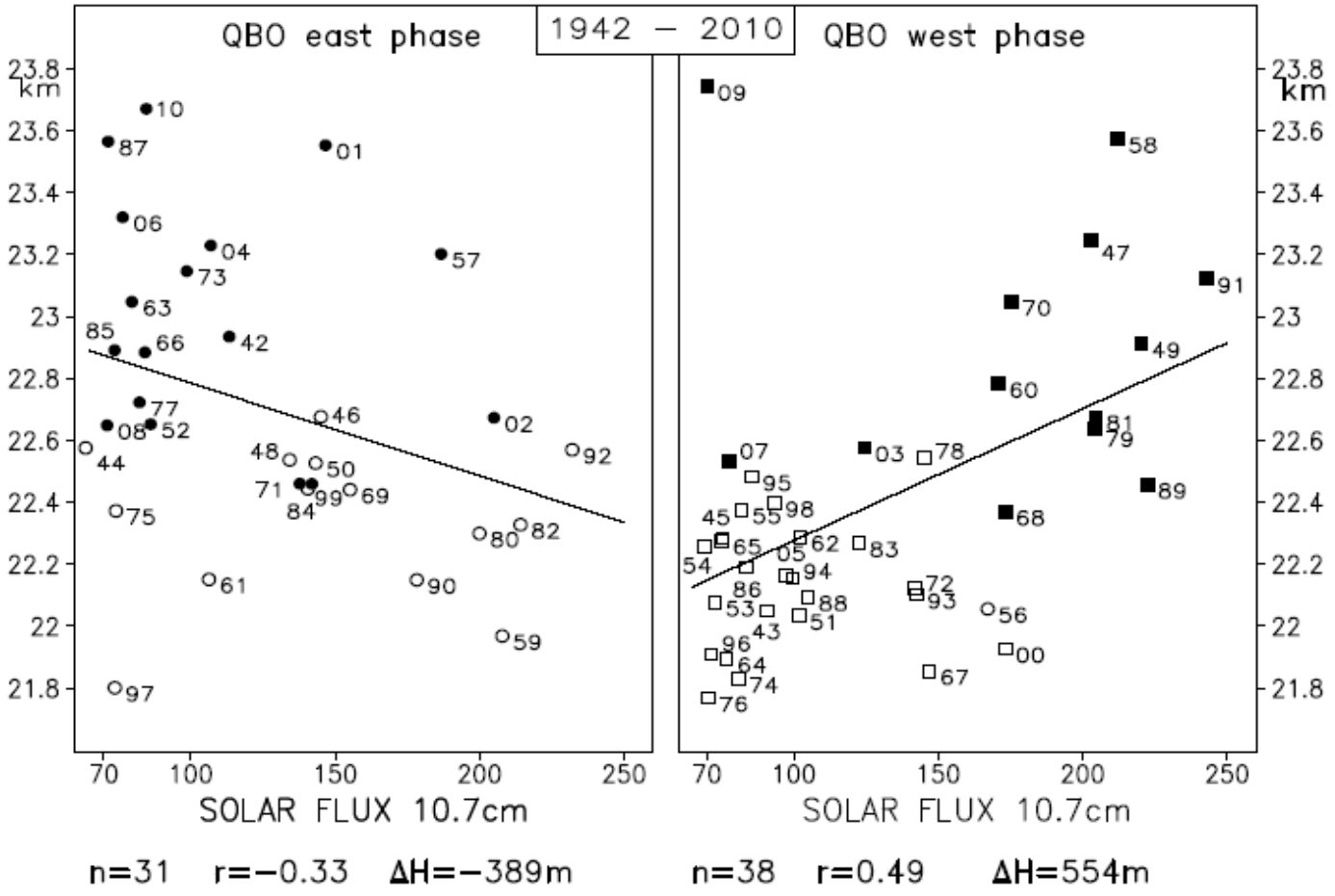


Reed (1961) and Veryard and Edbon (1964): The wind above the equator oscillates in direction with an average period of 26 months

(⇒ "quasibiennial")

The correlation between sunspot number and meteorological parameters depends on the phase of QBO

30 hPa geopotential height over the North pole as a function of solar UV

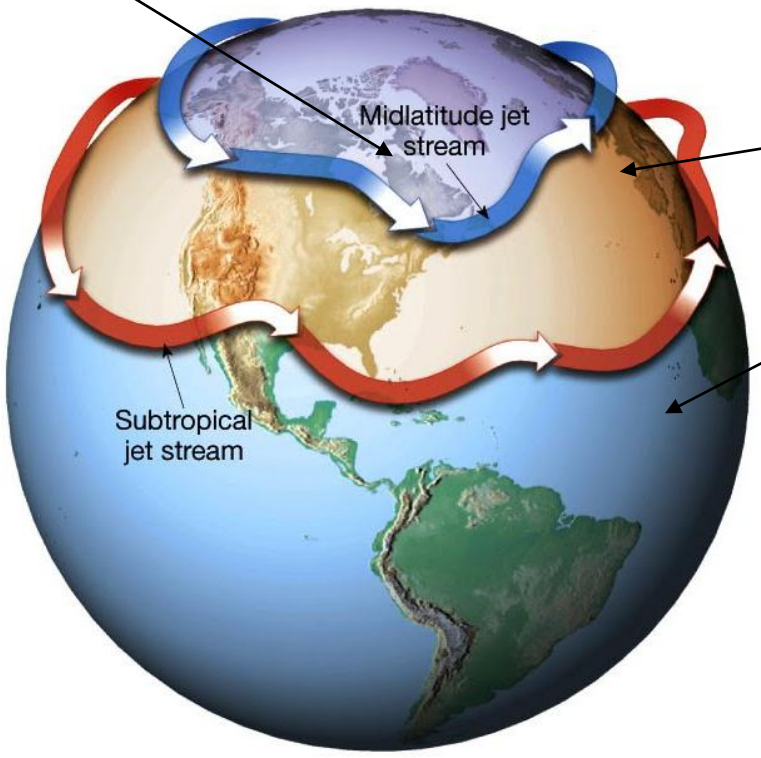


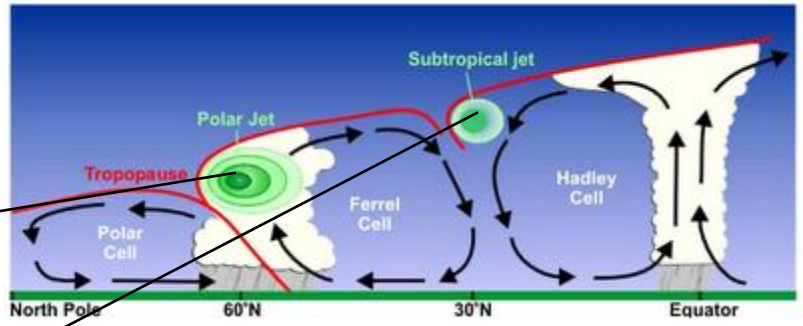
Van Loon and Labitzke, 1994

Atmospheric waves

Planetary (Rossby) waves

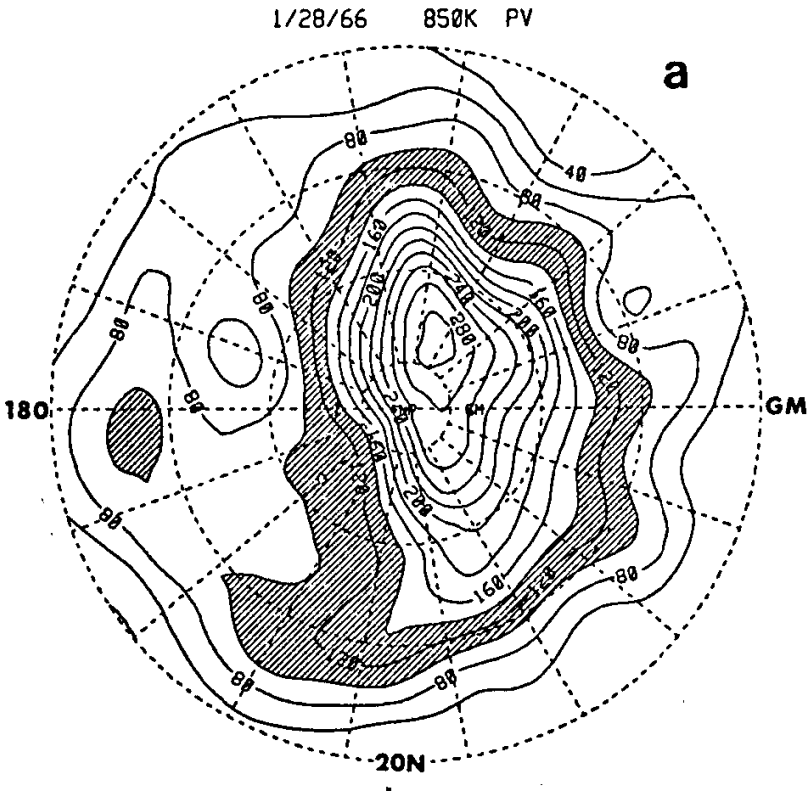
Tropospheric polar vortex





The jet streams meander about their average position due to the latitudinal variation of the Coriolis force and orography

Stratospheric polar vortex



In winter:

- No sunlight to heat the ozone over the pole
- The stratosphere cools
- Thermal disbalance with the lower latitude stratosphere
- Pressure difference (+ Coriolis force) = strong jet stream (“Polar jet”)
- Contained within it – a strong vortex (“Polar vortex”)

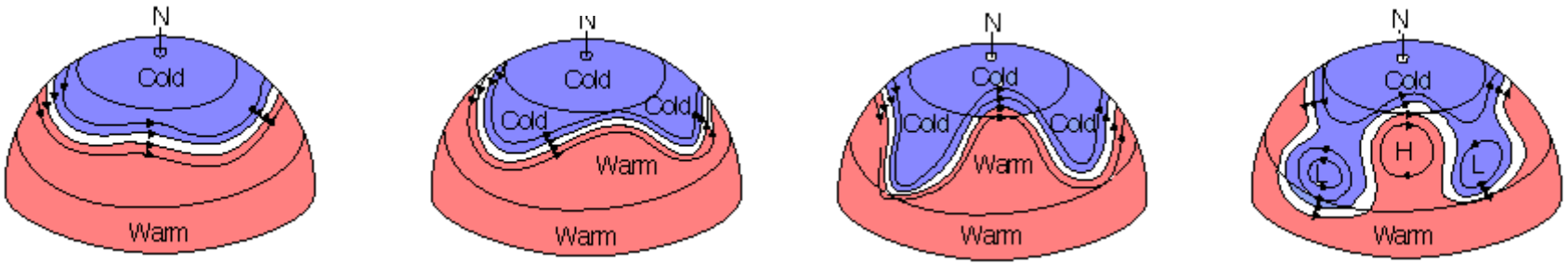
Importance and relation with climate

cold stratosphere

- strong stratospheric vortex
- strong tropospheric vortex
- strong and straight polar jet
- unsettled, mild and wet weather

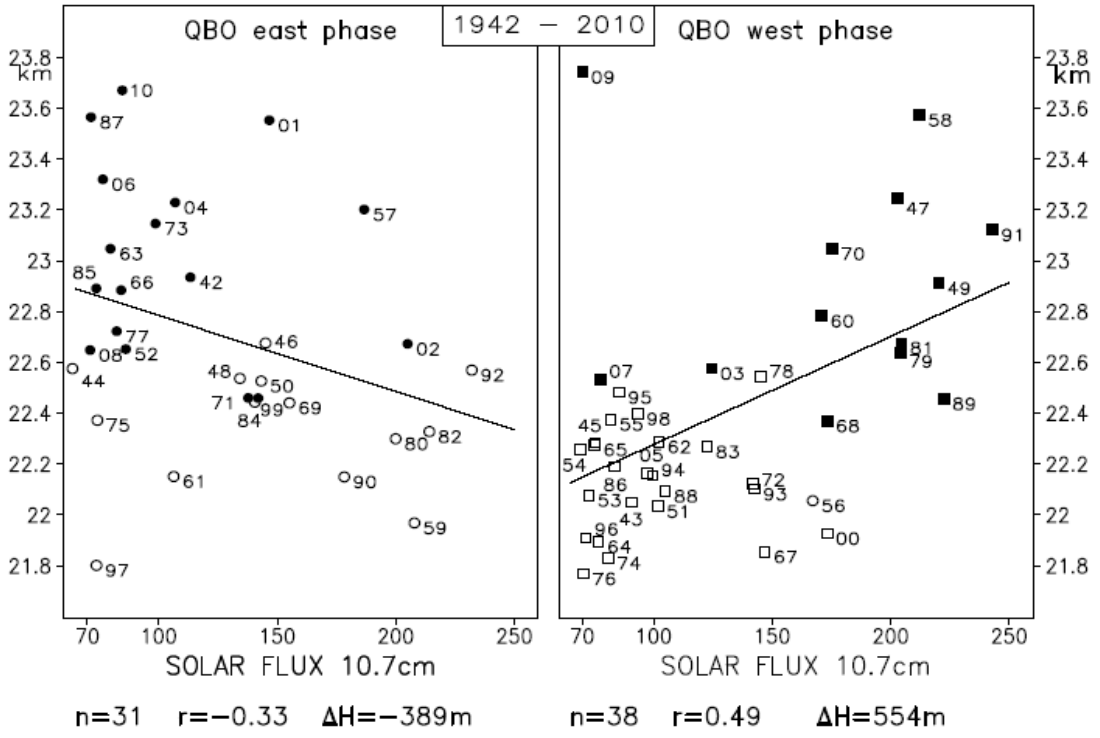
warm stratosphere

- weak stratospheric vortex
- weak tropospheric vortex
- weak and meandering polar jet
- persistent anomalies, hot and cold waves



More and longer blocking events for solar minima (Barriopedro et al., 2008)

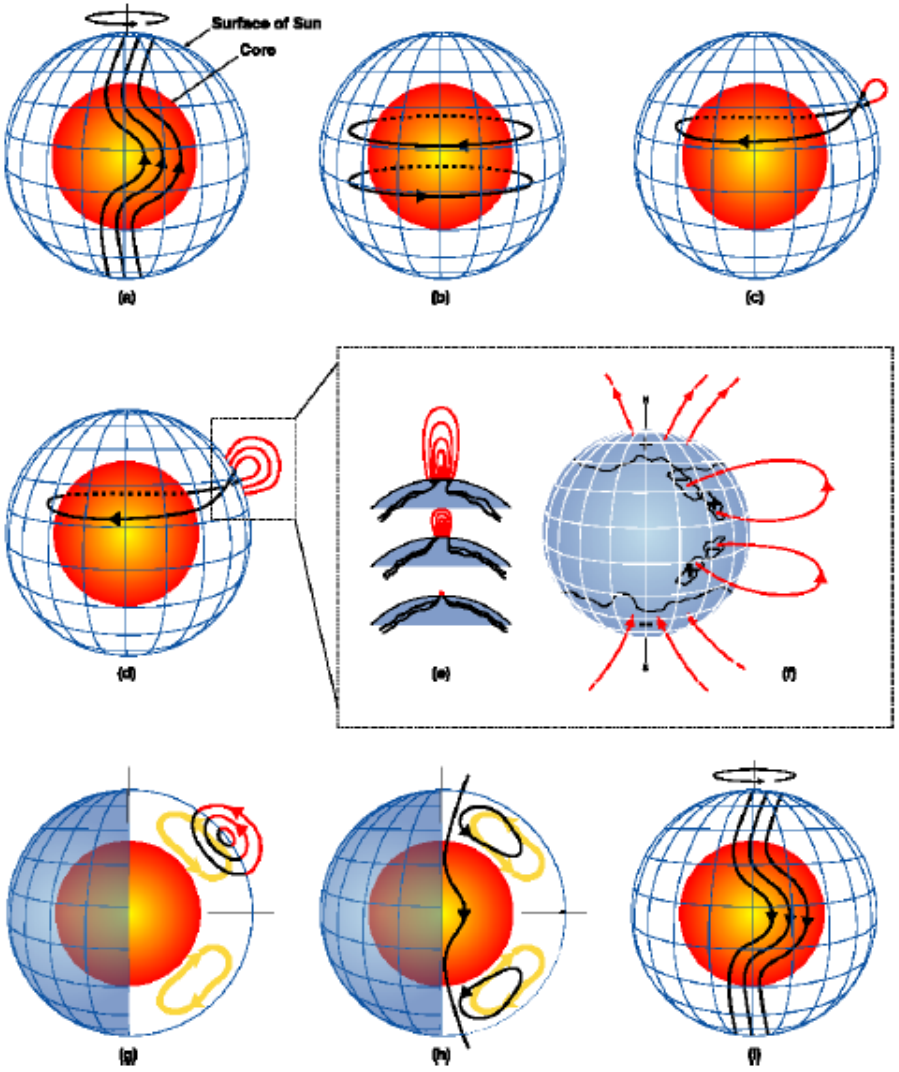
Combined QBO/solar influence on the polar votex



The vortex is stronger and colder in Smin/QBO-W and in Smax/QBO-E years

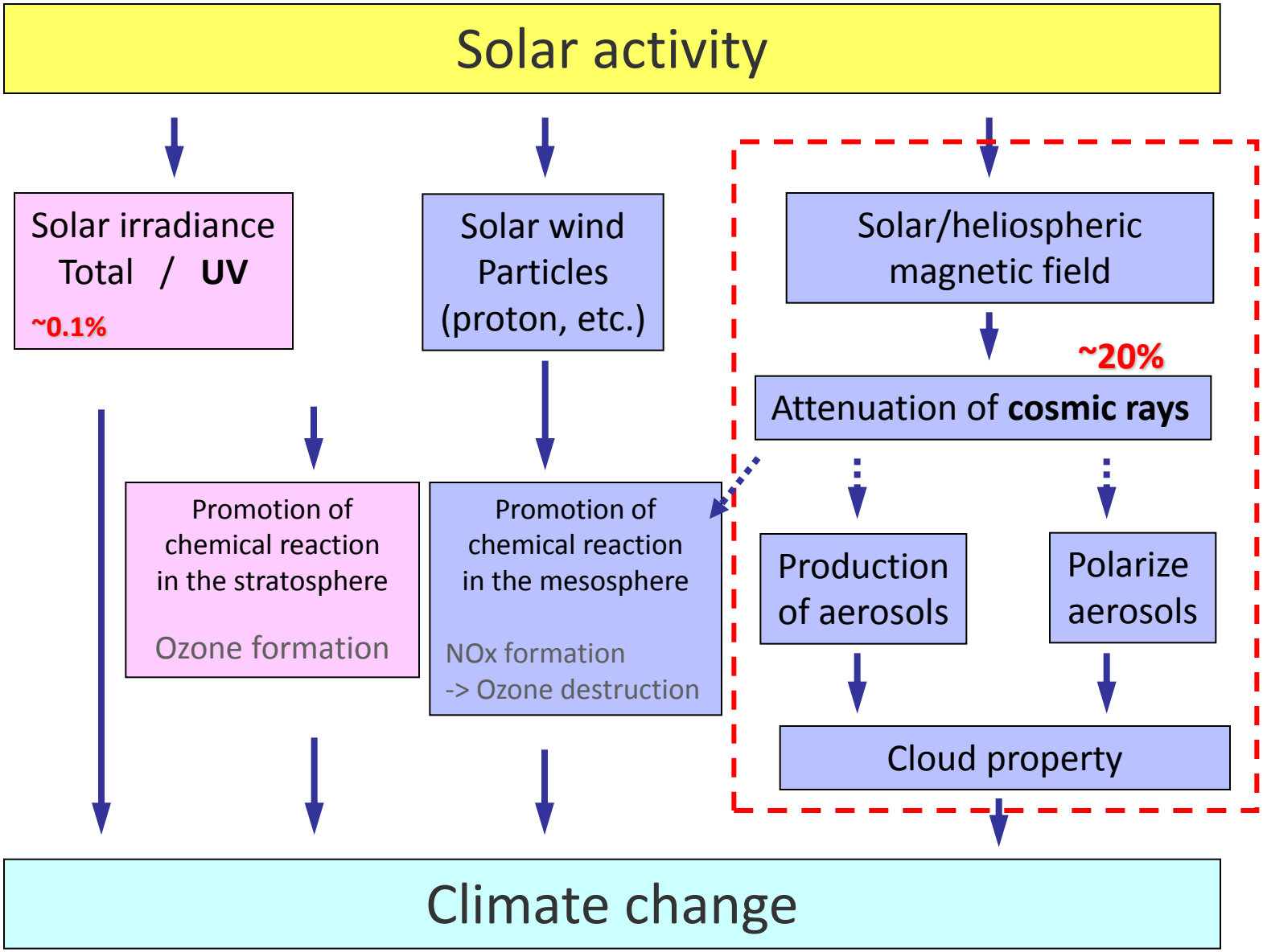

SOLAR ACTIVITY BASICS AND
POSSIBLE RELATIONS WITH
CLIMATE

solar dynamo

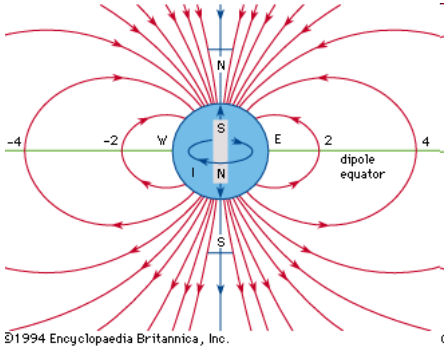


transforms the solar
poloidal field
(sunspot min)
into toroidal field
(sunspot max)
and back into
poloidal field with
the opposite
magnetic polarity
(next sunspot min)

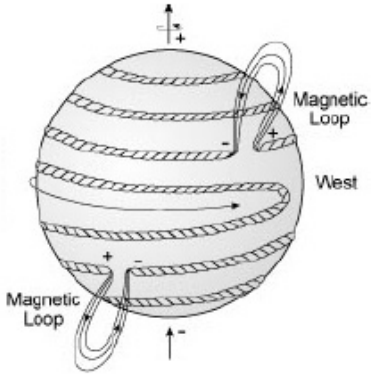
Possible mechanisms of solar influence on climate change



Two types of solar magnetic fields:

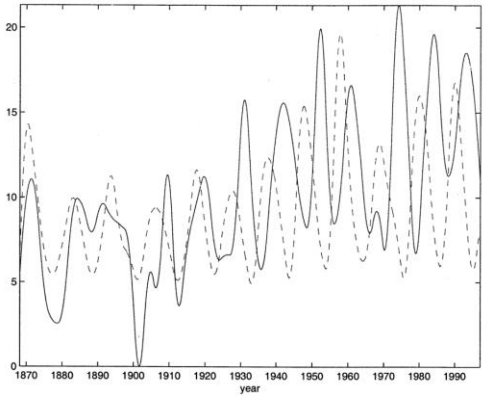


poloidal



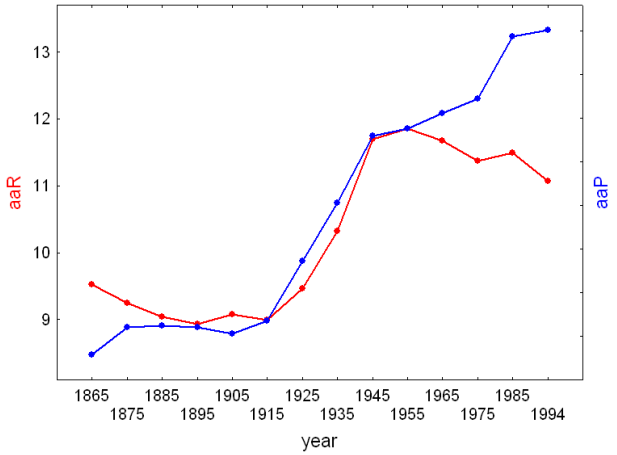
toroidal

Different solar cycle variations



(Ruzmaikin and Feynman, 2001)

Different long-term variations

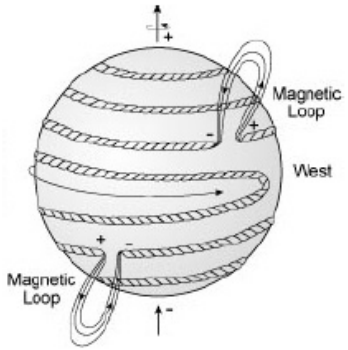


(Georgieva et al., 2012)

And possibly different influence on the Earth's system

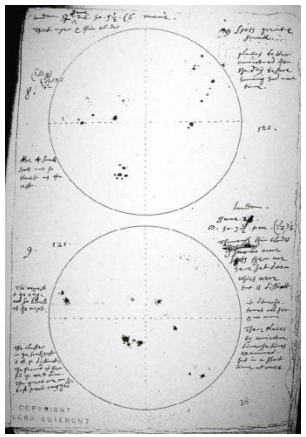
Two types of solar magnetic fields:
toroidal

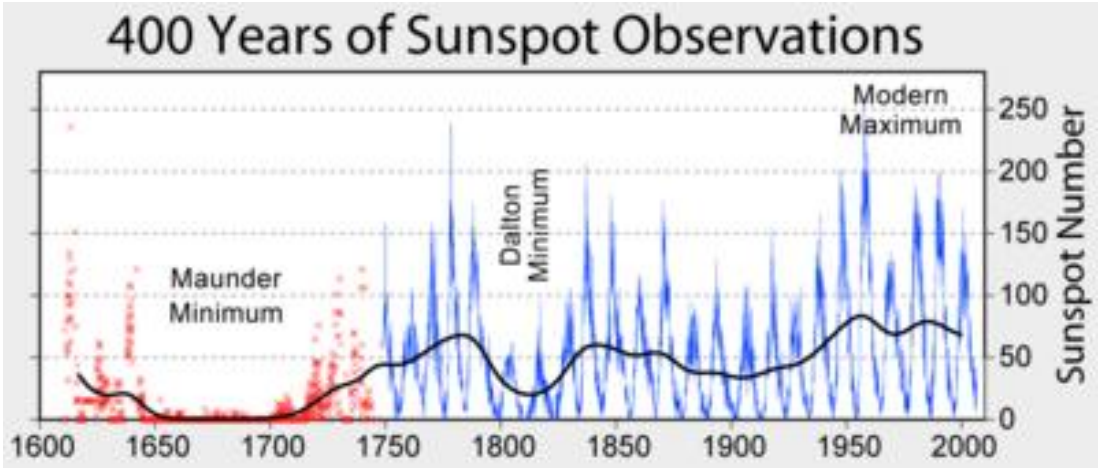
Solar toroidal field



Sunspots
are manifestation of the solar toroidal field

Thomas Harriot
8 December 1610



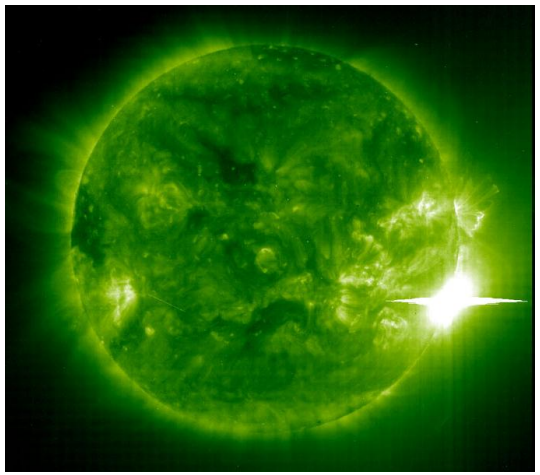


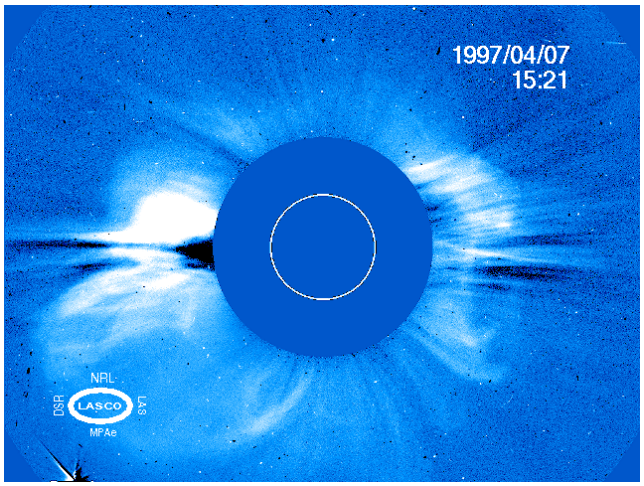
Often used as a measure of solar activity because of their long record, but they are manifestation of ONLY the toroidal field.

Relared geoeffective agents

Sunspots themselves have NO INFLUENCE WHATSOEVER on the Earth system

But their number and surface area are proportional to the number and intensity of solar flares and CME's



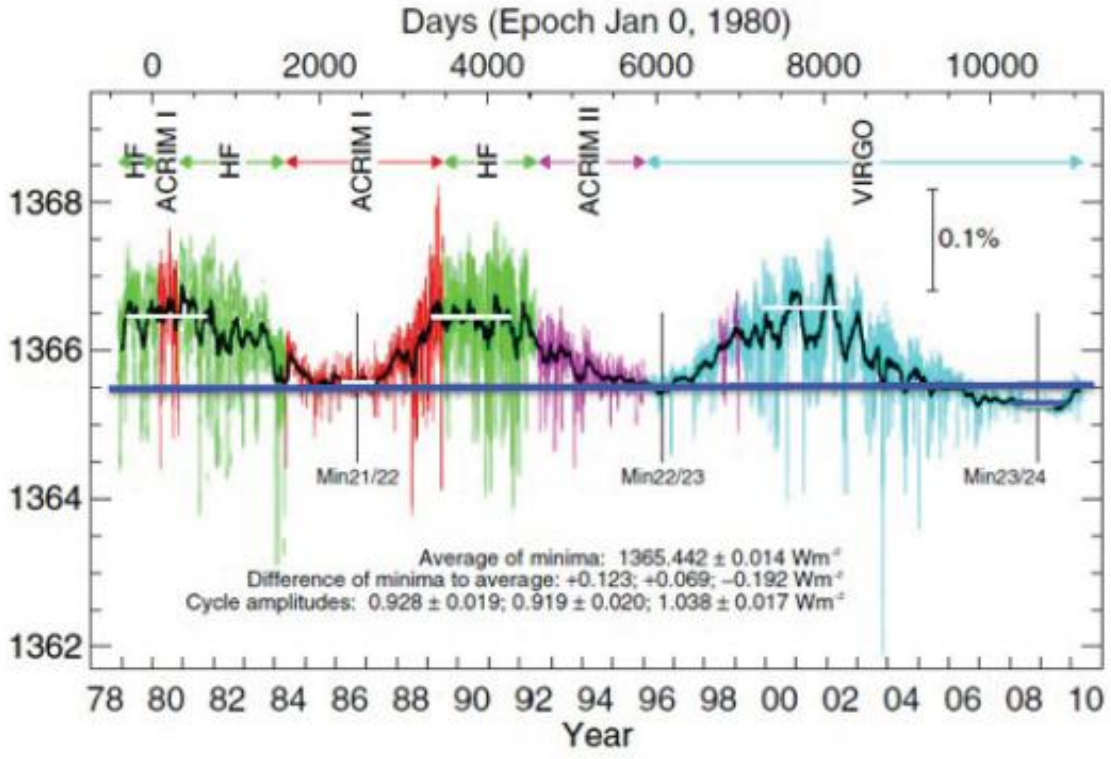


also manifestation of the solar toroidal field

Flares ionize the upper atmosphere

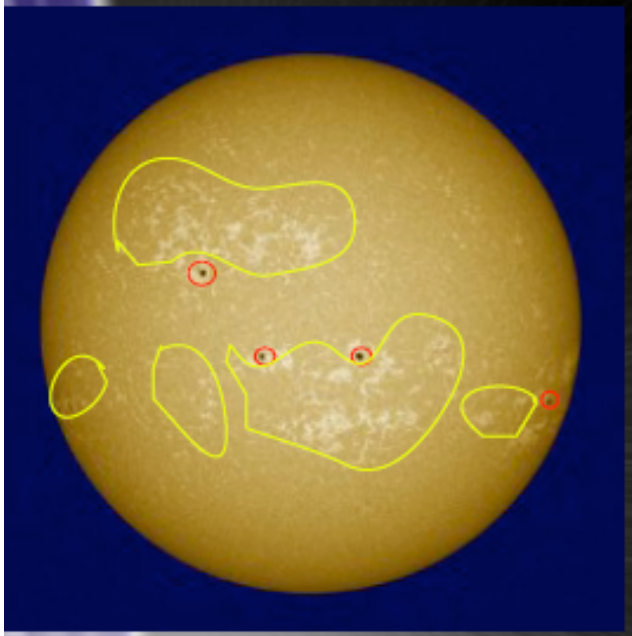
CMEs cause the strongest geomagnetic storms

sunspot number and area - proportional to solar irradiance important for climate



Total Solar Irradiance (TSI) increases by ~0.1% at sunspot maximum: the more dark sunspots there are on the Sun, the brighter it gets.

MECHANISM AND MODELS OF IRRADIANCE VARIATION



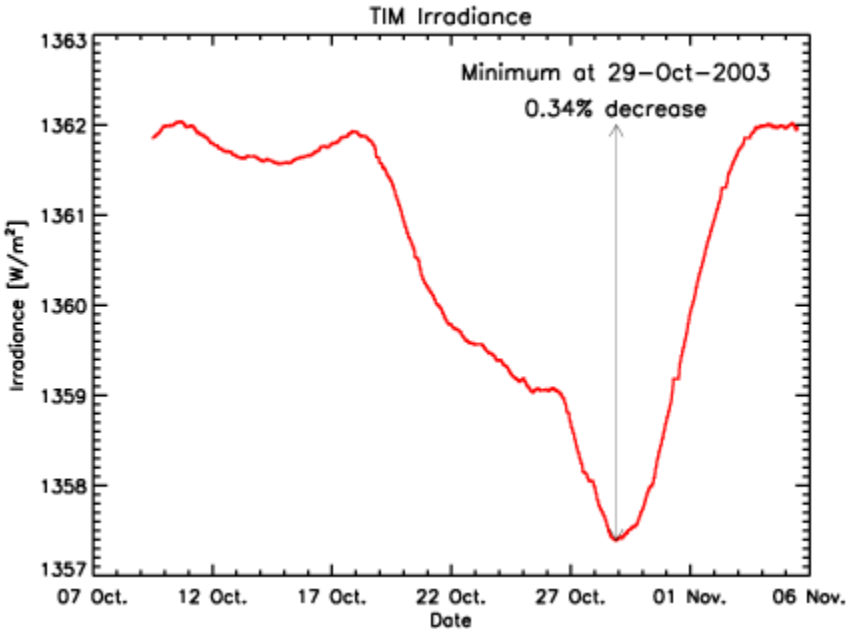
Changes in the surface structure due to the evolution of the photospheric magnetic field

Irradiance = Quiet Sun brightness
+ darkening due to sunspots
+ brightening due to faculae and the network:

$$S_{tot}(t) = S_{QS} + \Delta S_s(t) + \Delta S_f(t) + \Delta S_n(t)$$

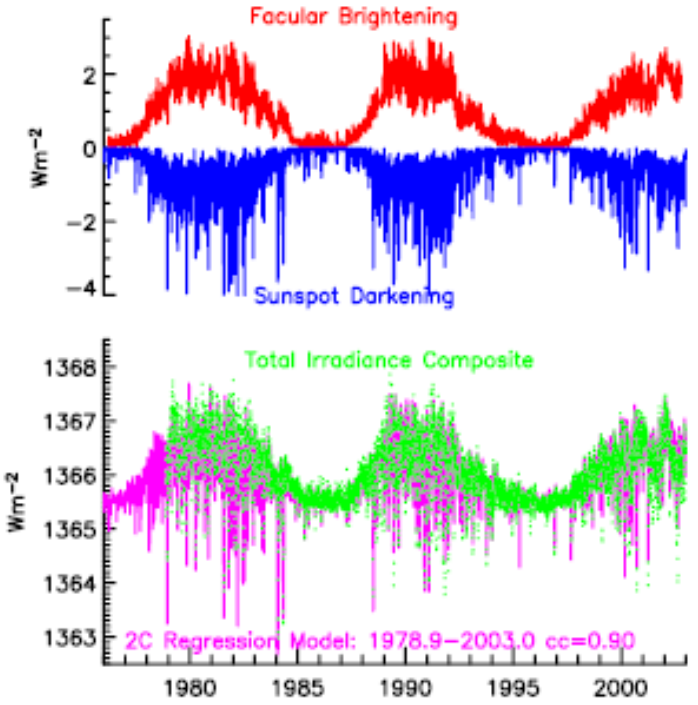
Krivova, COST ES1005 (2011)

More sunspots = stronger toroidal field = brighter faculae



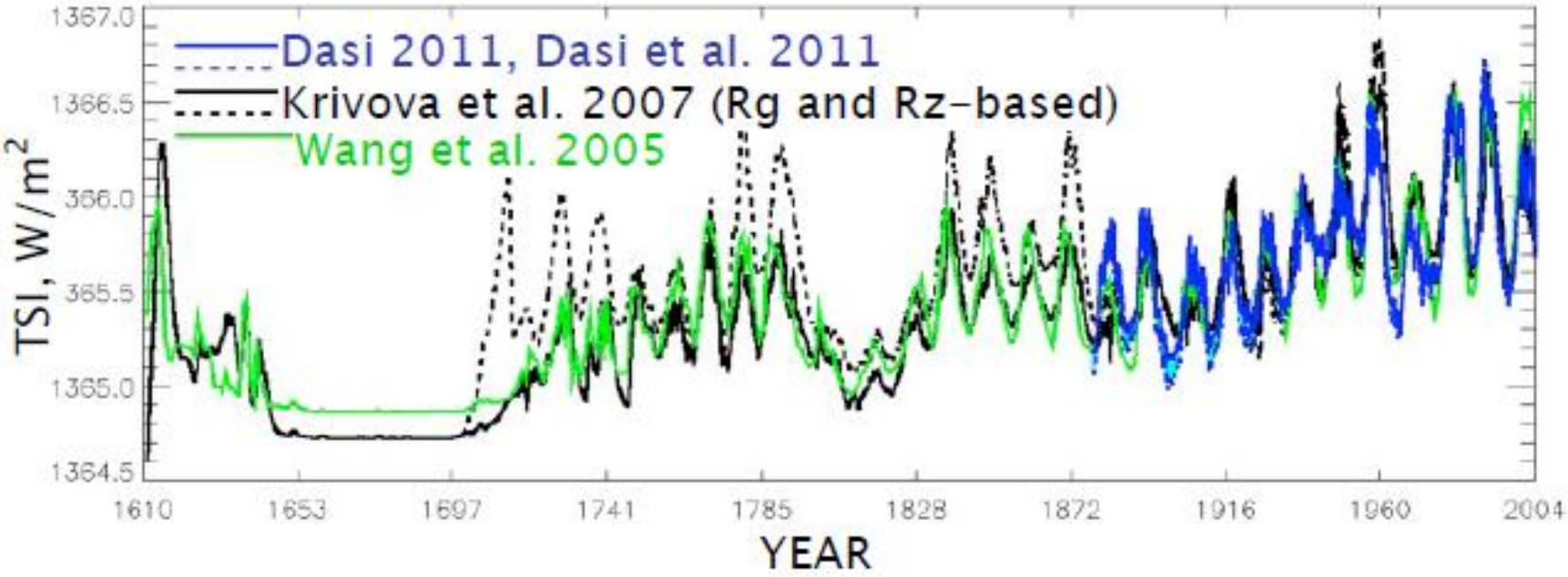
TSI decrease during the passage of two large sunspot groups

But bright faculae "outnumber" and outlast dark sunspots and overcompensate the sunspot irradiance deficit



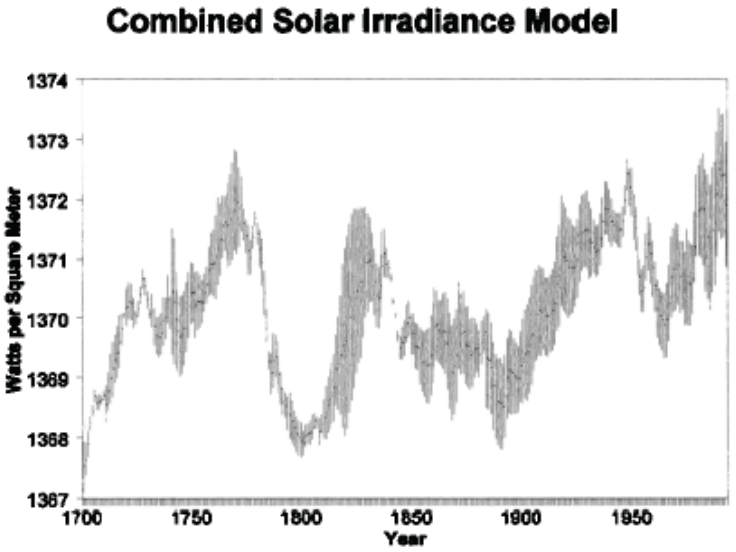
Courtesy J. Lean

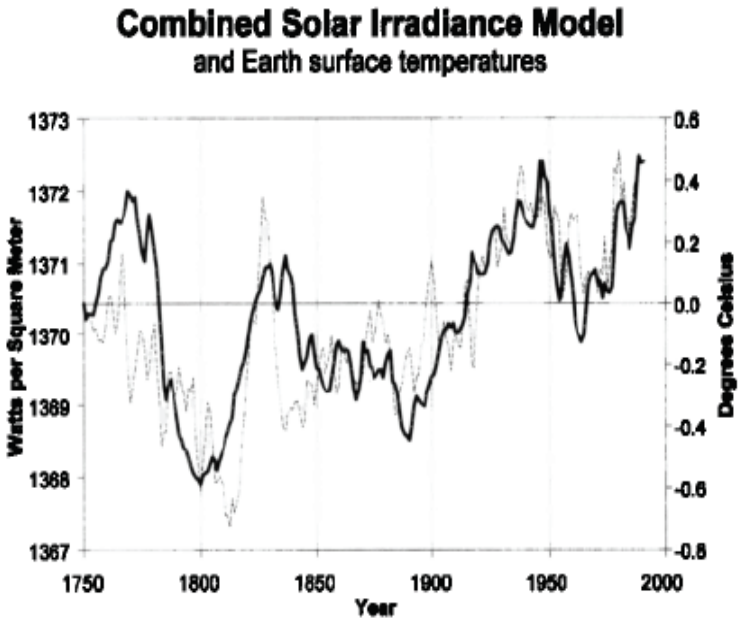
Reconstruction of total solar irradiance (TSI) from sunspot numbers



TSI varies by ~ 0.1% in the 11-year sunspot cycle and by ~0.6% since 1700

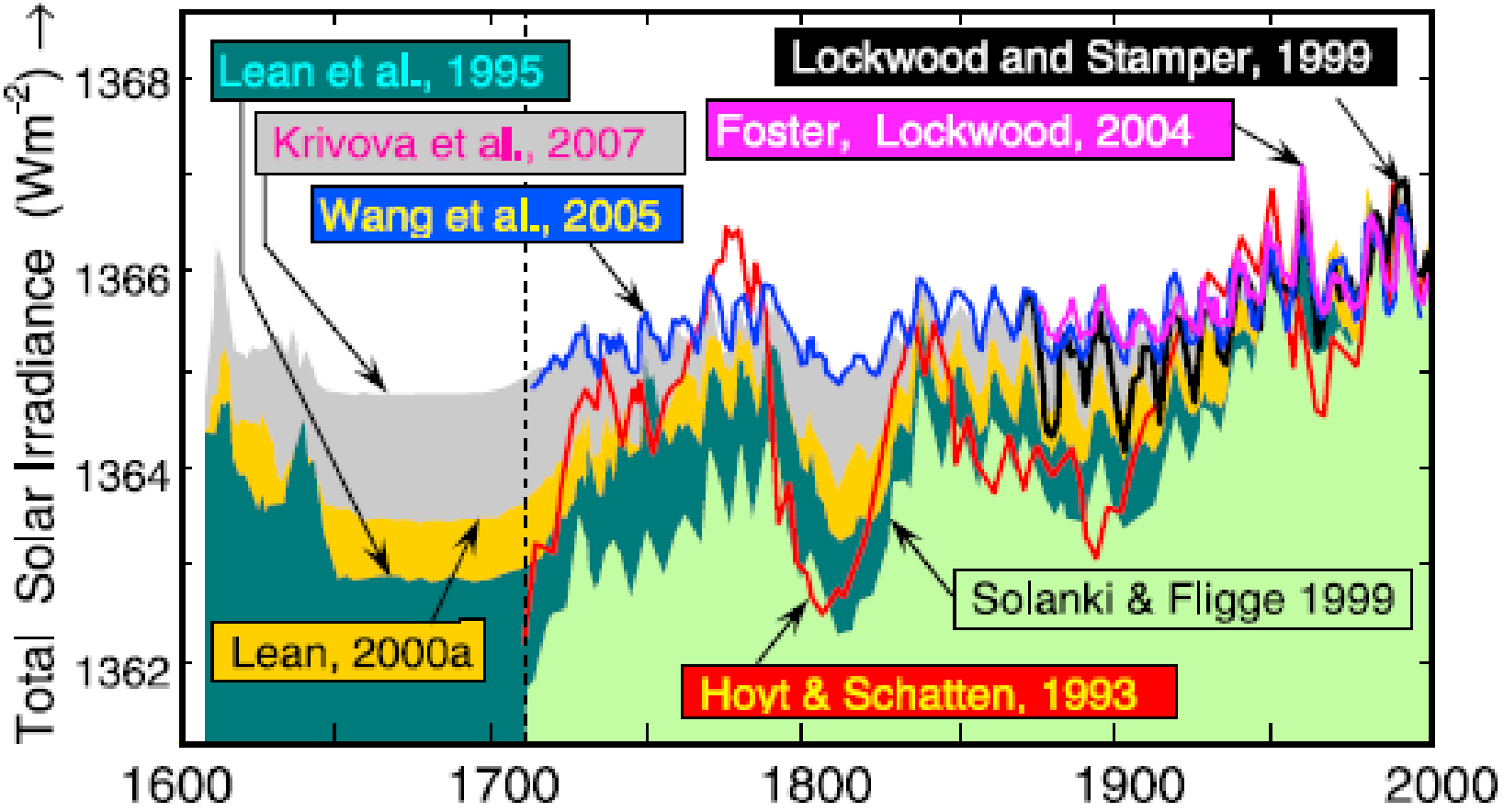
Another approach – using the solar cycle length (Hoyt and Schatten, 1993)





Physical basis: solar cycle length ~ speed of meridional circulation ~ solar magnetic fields

Different reconstructions



TSI effect on climate: Possible mechanisms

1. Direct effect: $\Delta T = \lambda * \Delta TSI$

ΔTSI – variation in the incoming radiation at the top of the atmosphere

λ – climate sensitivity to variations in TSI

Estimation:

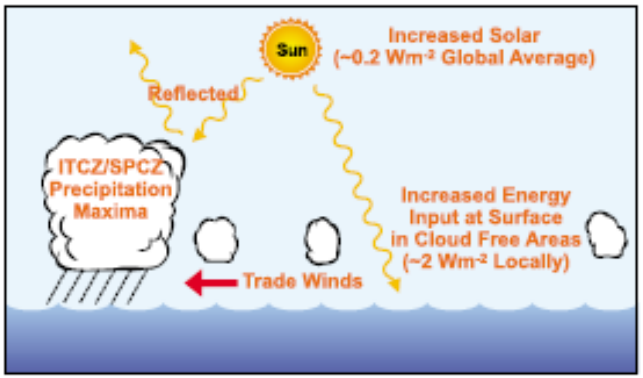
$\Delta TSI = \sim 0.17\ W/m^{-2}$ in the 11-year cycle

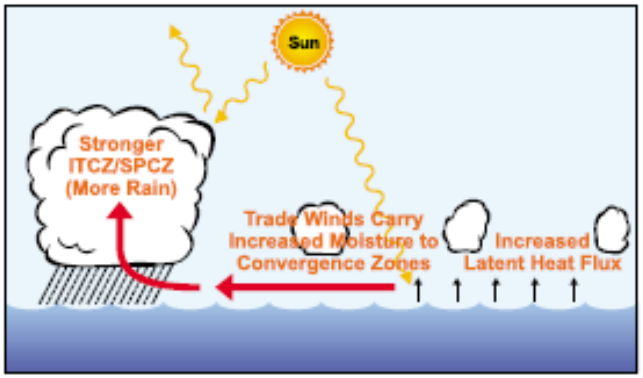
$\lambda = 0.3 – 1.0\ K\ (W\ m^{-2})^{-1}$

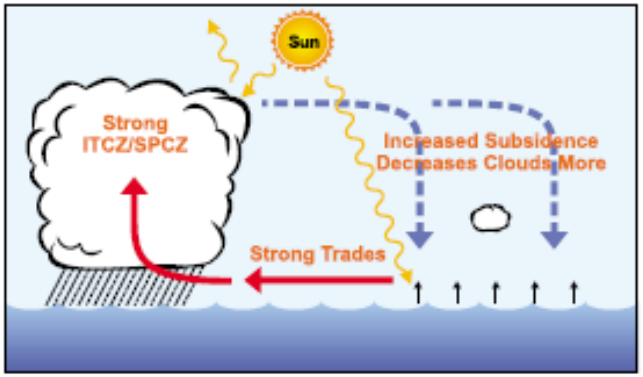
$\Rightarrow \Delta TSI = 0.017\ K$ (for $\lambda = 0.5$ - IPCC) too small!

$\Rightarrow$ the mechanism is more complucated

2. Bottom-up mechanism







Increased solar forcing during Smax on cloud-free subtropical oceans

⇒ increased evaporation from tropical oceans ⇒ decreased SST there

⇒increased trade winds and increased moisture carried to intertropical conve ence zone

⇒ intensified precipitation and upward vertical motions into precipitation zones

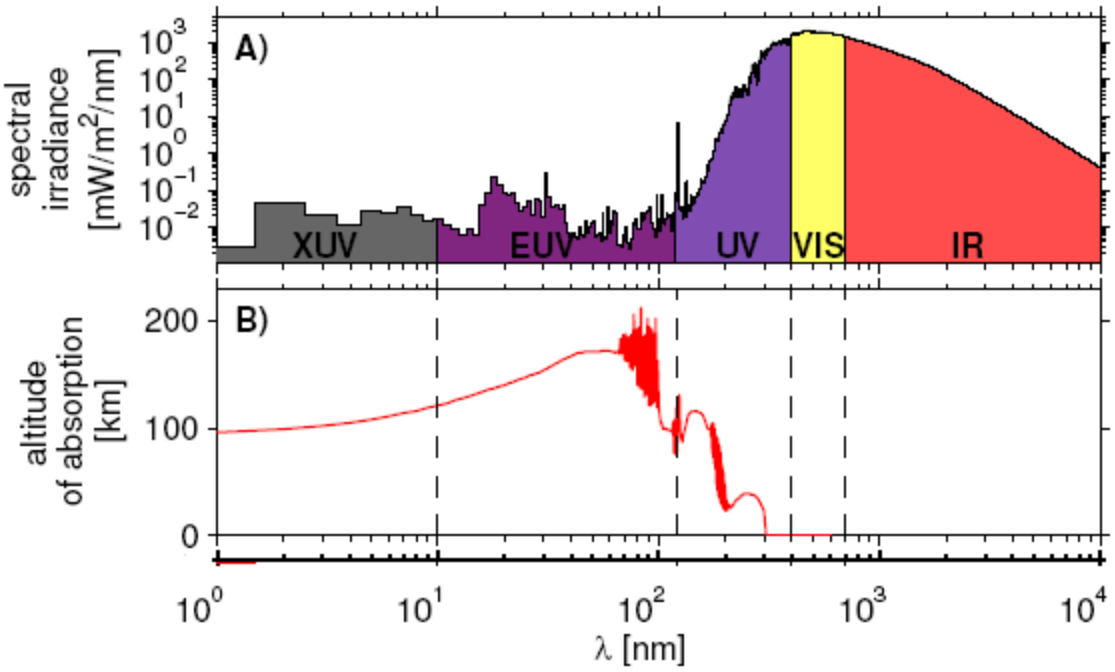
⇒ stronger Hadley and Walker circulations

⇒ stronger subsidence in subtropics

⇒ further reduced clouds and further increased solar forcing… and so on

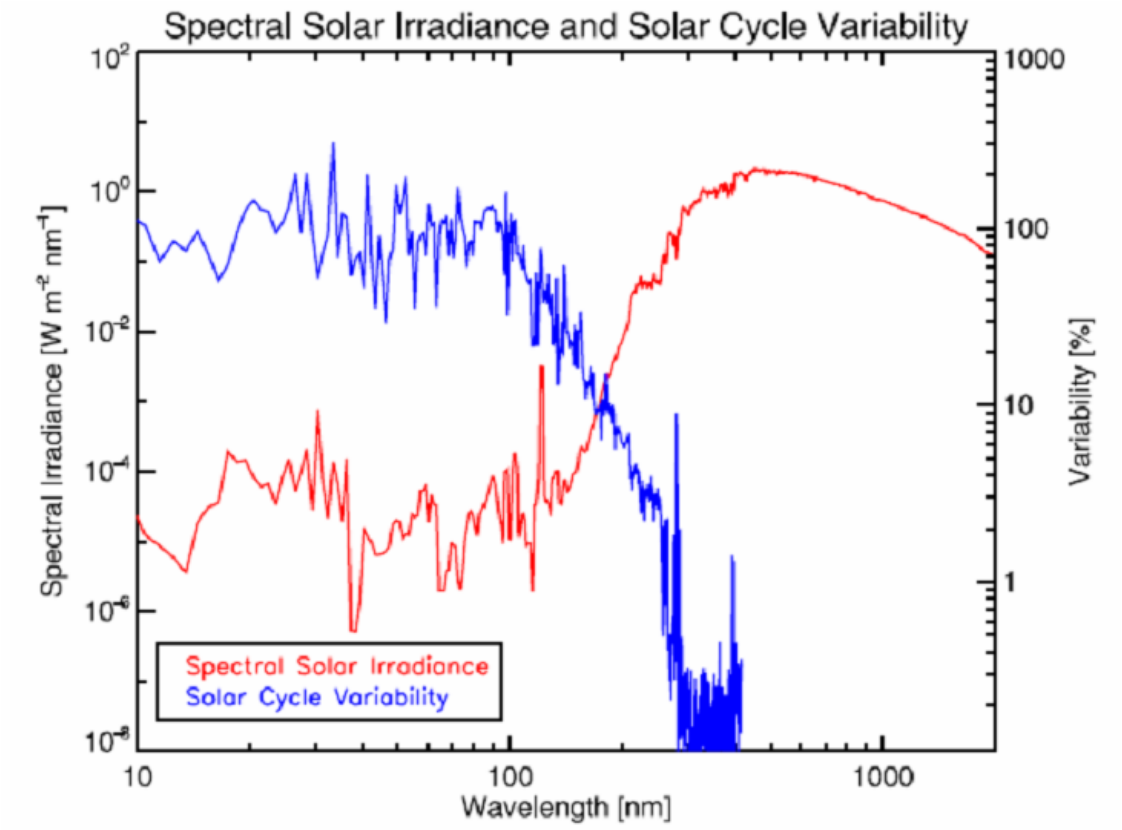
van Loon, Meehl, Cubasch

Solar spectral irradiance



visible and near infrared irradiance reach the Earth's surface and troposphere, UV is absorbed in the troposphere and stratosphere, EUV and XUV don't reach below the thermosphere

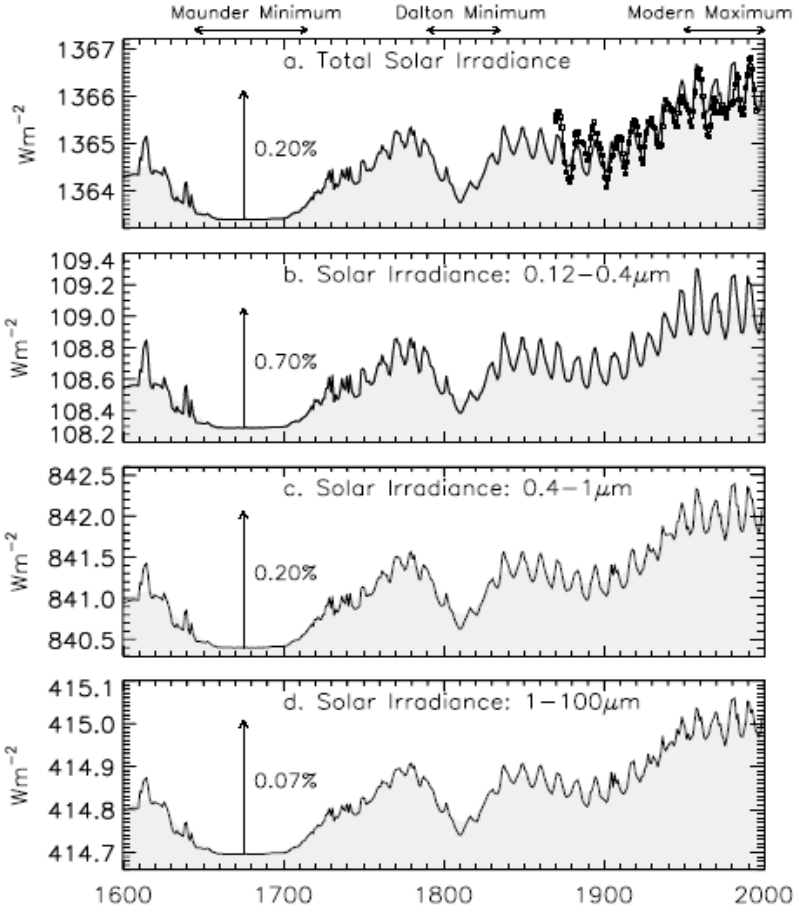
Much more variability at shorter wavelengths



Solar cycle variations

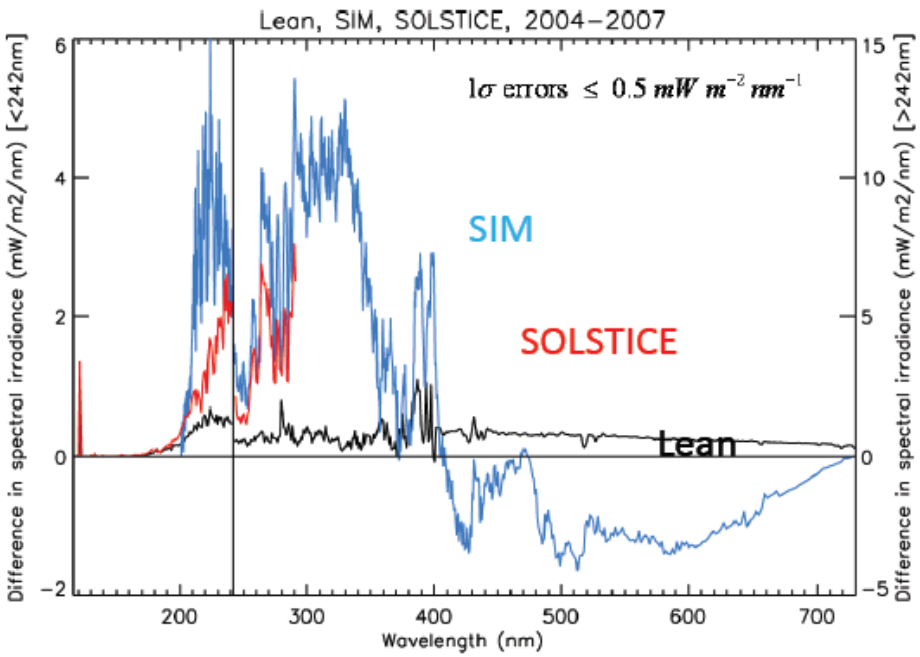
Domingo et al. (2009)

Long-term variations



Lean et al (2001)

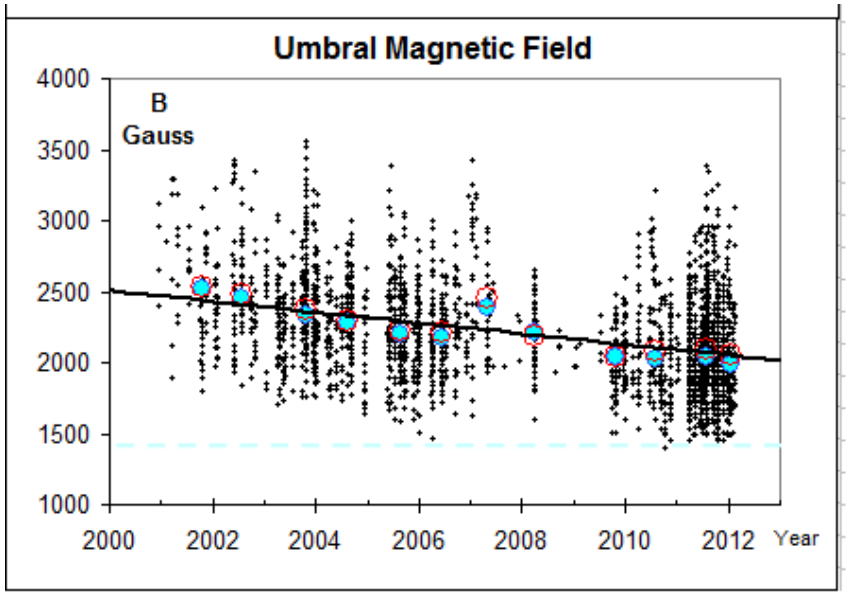
Spectral differences 2004-2007



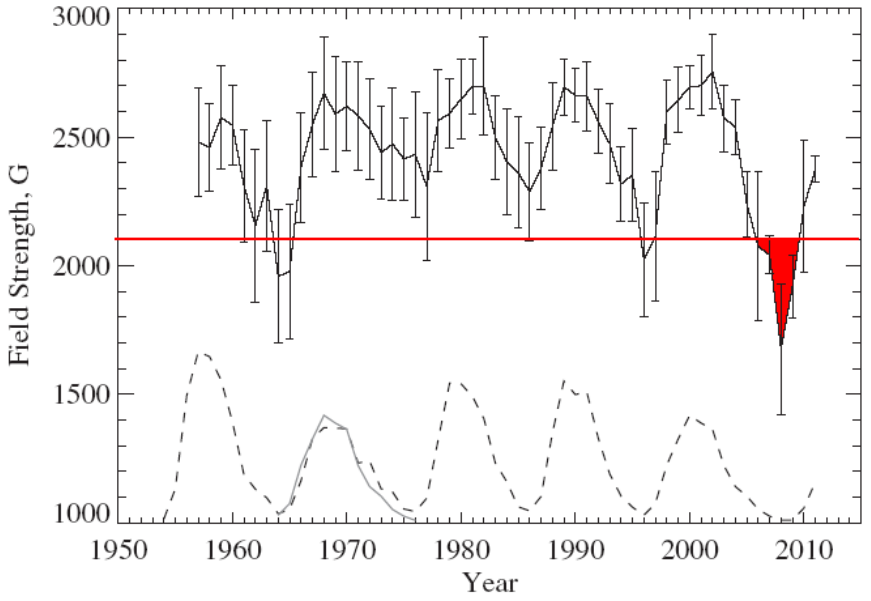
Necessary to revise the model!

The models are based on the number and area of sunspots and don't account for magnetic field

Penn and Livingston (2010)



Pevtsov et al. (2011)



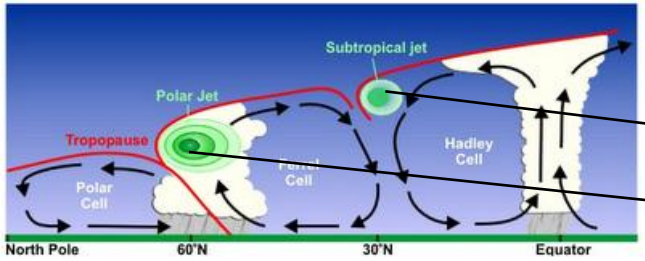
Secular decrease in the sunspot magnetic field

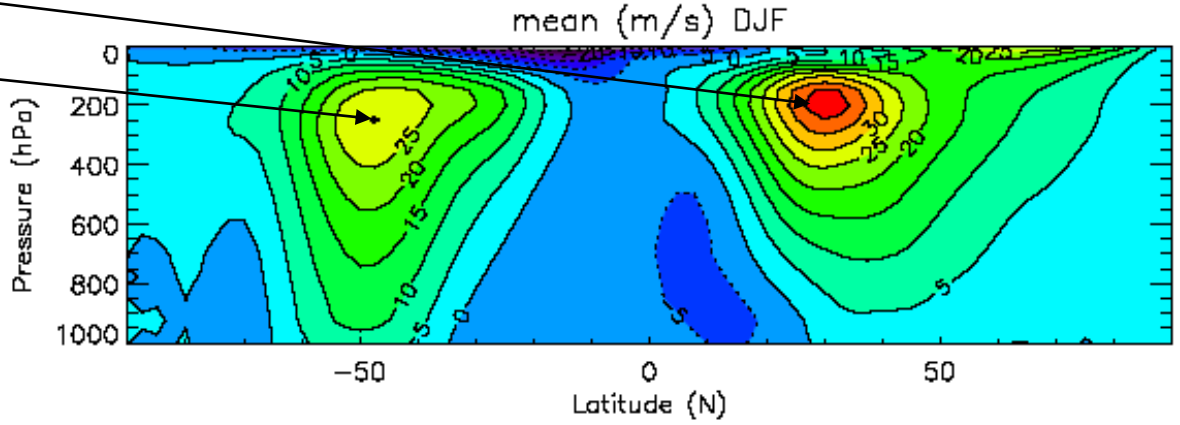
the mean field strength may reach the **threshold 1500 G** value in 2022

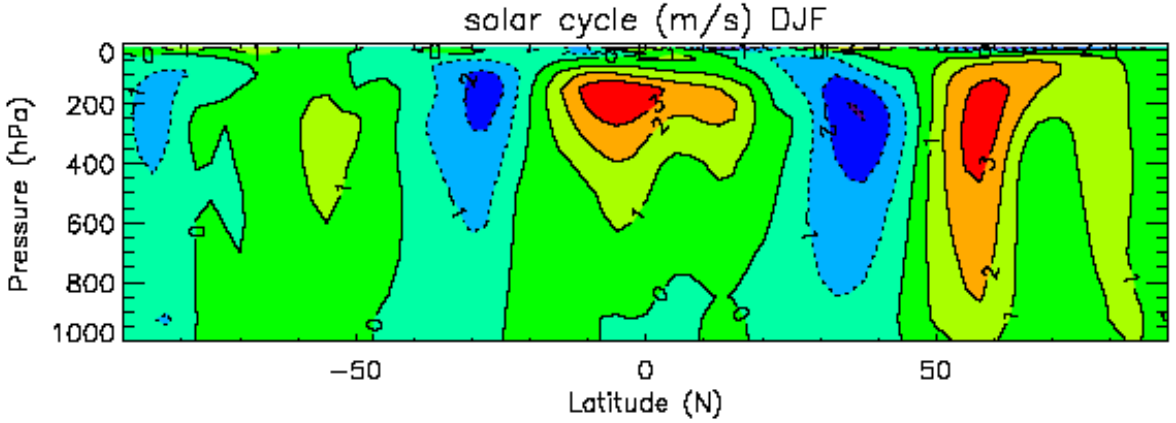
Solar cycle variations in sunspot magnetic field

Secular variations in the field in sunspot min

SSI effect on climate: Possible mechanism





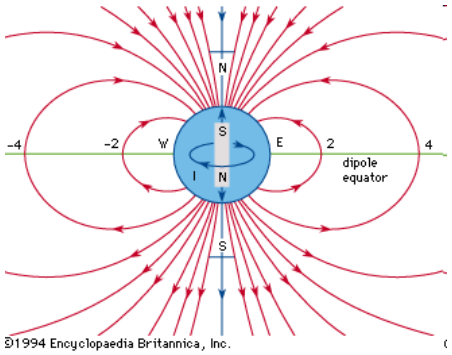


Changes in circulation due to the nonuniform heating of the stratosphere:

Broadening and weakening of Hadley cells

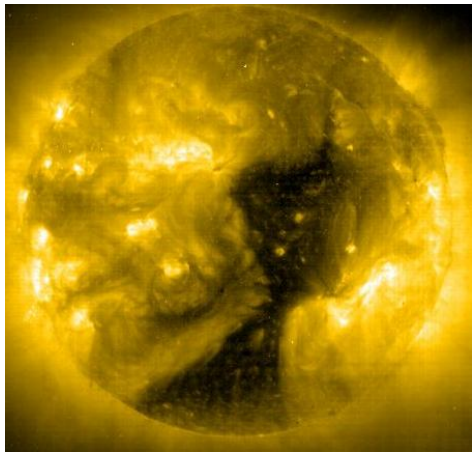
Two types of solar magnetic fields:
poloidal

Solar poloidal field

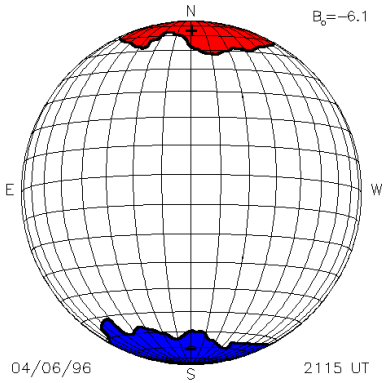


Its manifestation are the solar coronal holes – areas of lower temperature

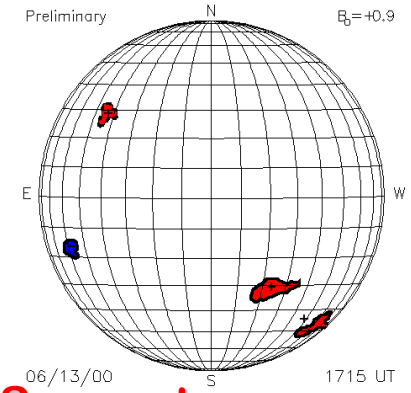
$\Rightarrow$ darker in X-rays



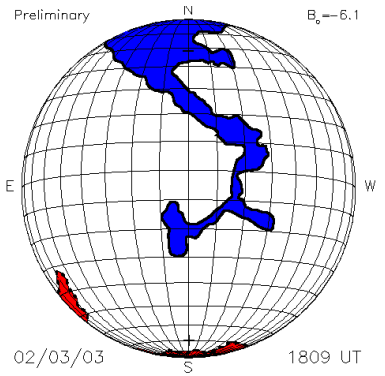
Areas of OPEN magnetic field lines



Sunspot min:
large polar coronal holes; no coronal holes at low latitudes



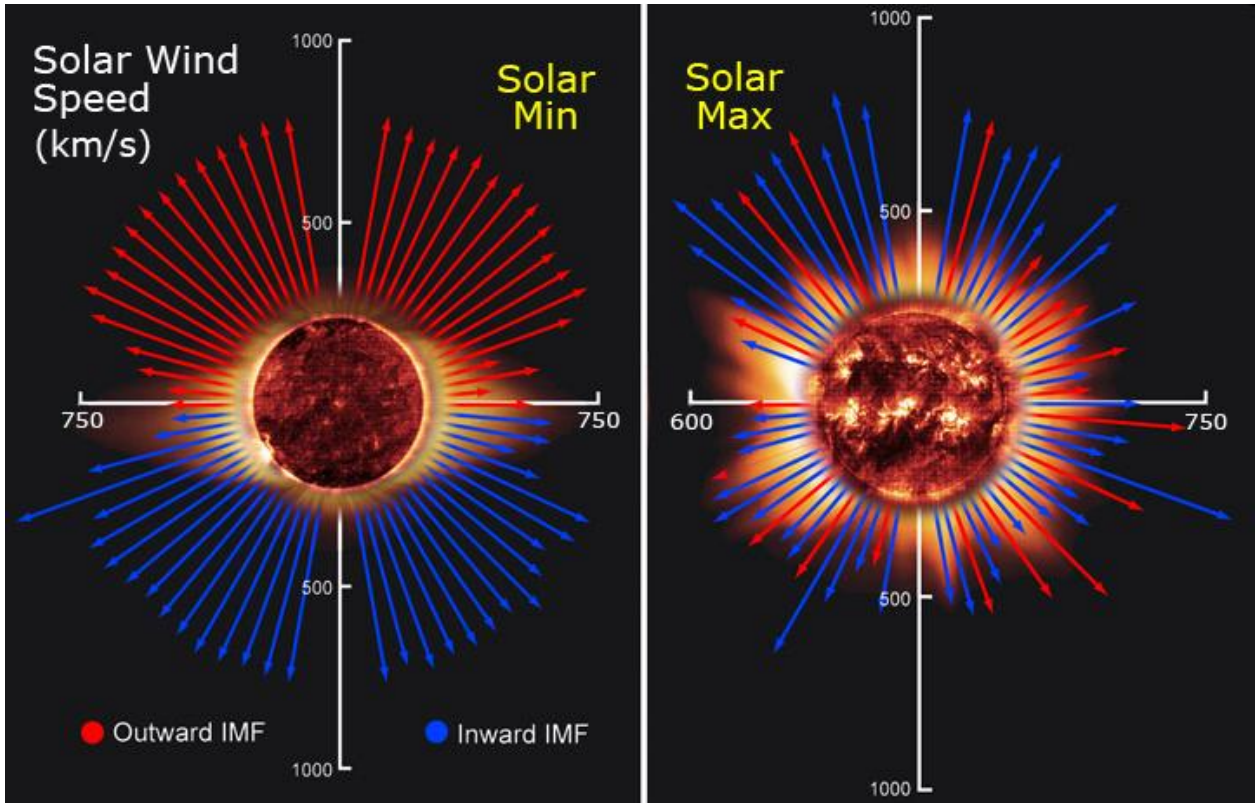
Sunspot max:
small scattered short-living coronal hole at all latitudes



Sunspot declining phase:
big long-lasting holes at all latitudes

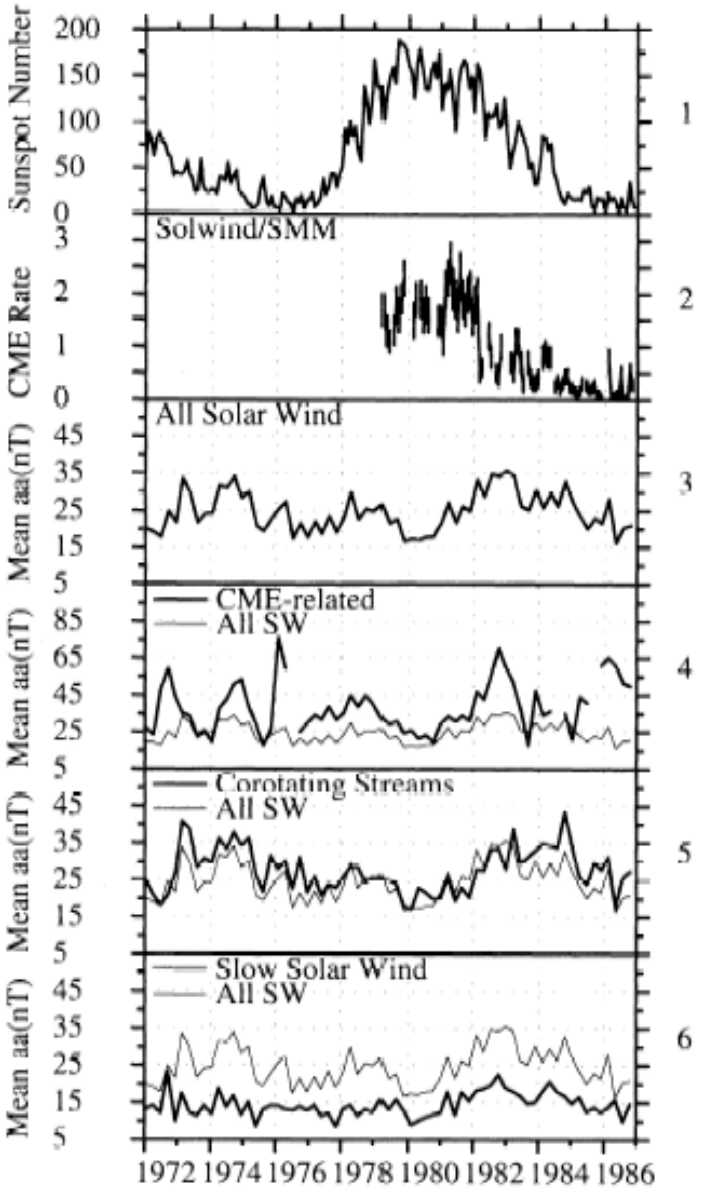
Related geoeffective agents

High speed solar wind streams (>500 km/s)



Cause recurrent geomagnetic storms

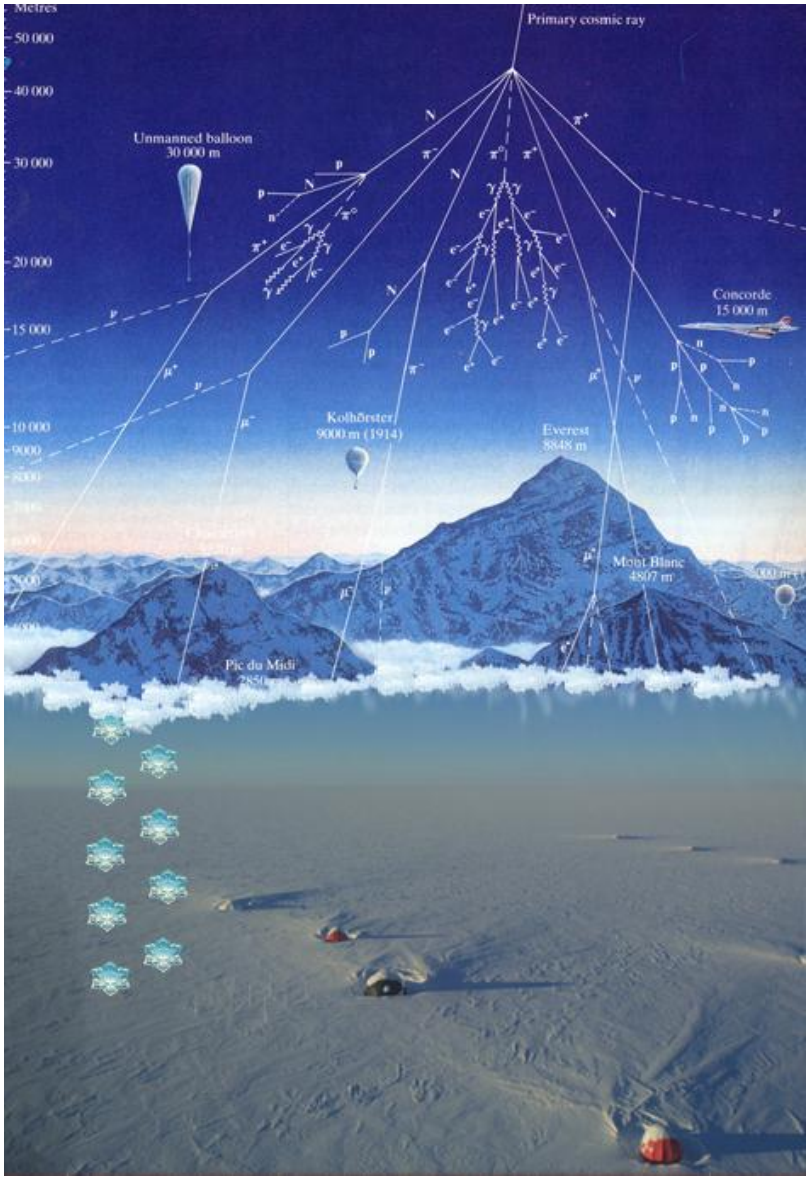
Geomagnetic activity



Poloidal field-related solar agents provide the main impact to **geomagnetic activity**

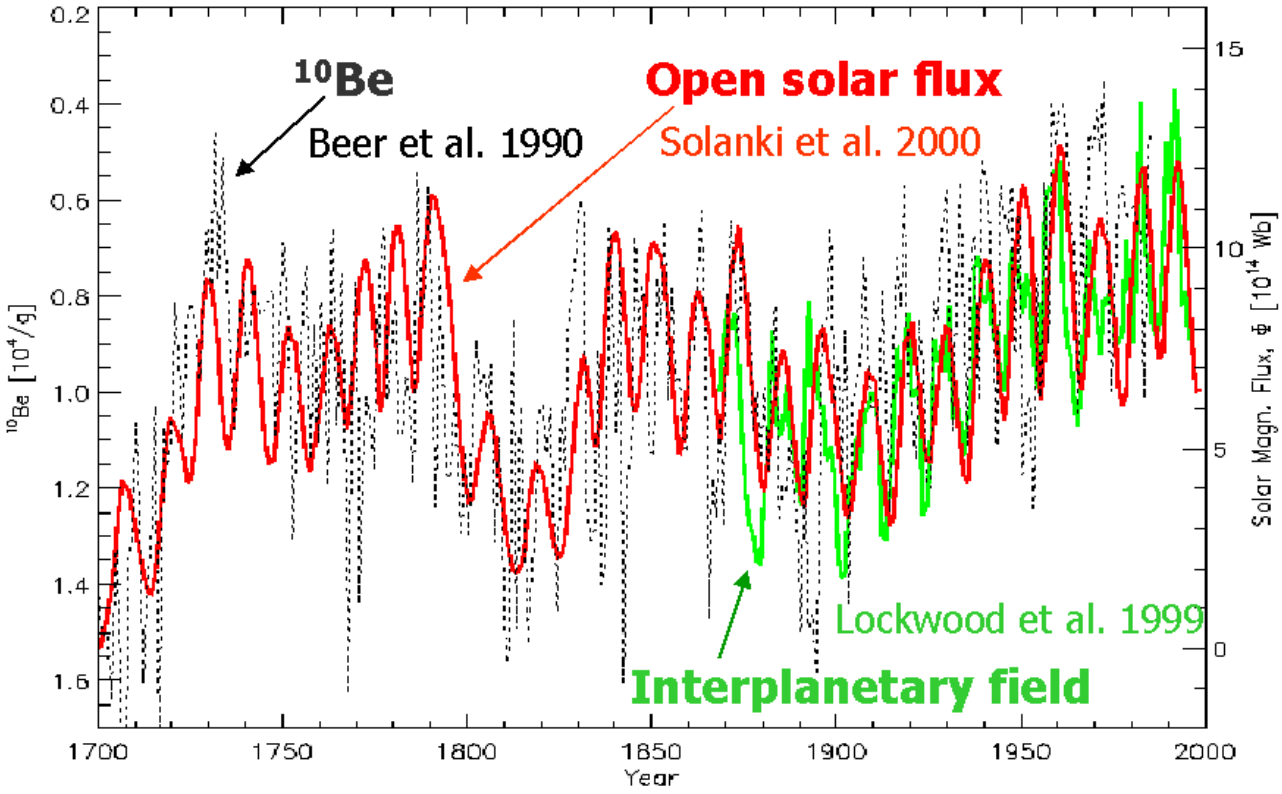
⇒ Records of **geomagnetic activity** can be used to reconstruct **solar poloidal (open flux) field**

Modulation of galactic cosmic rays

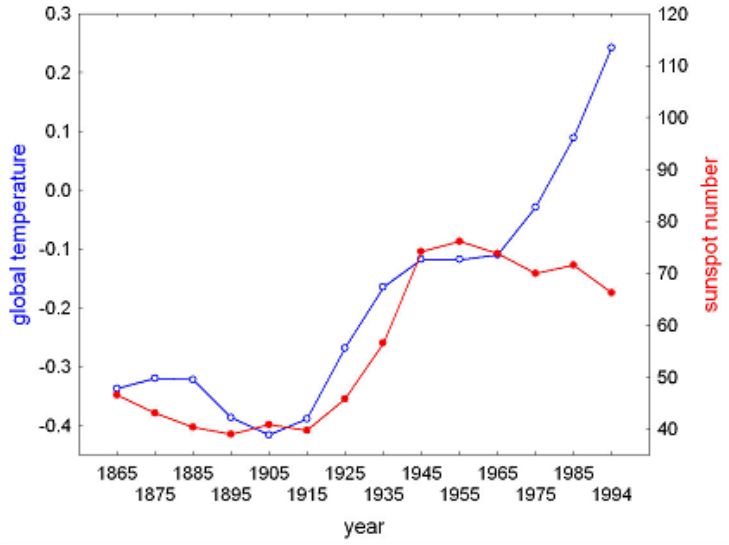


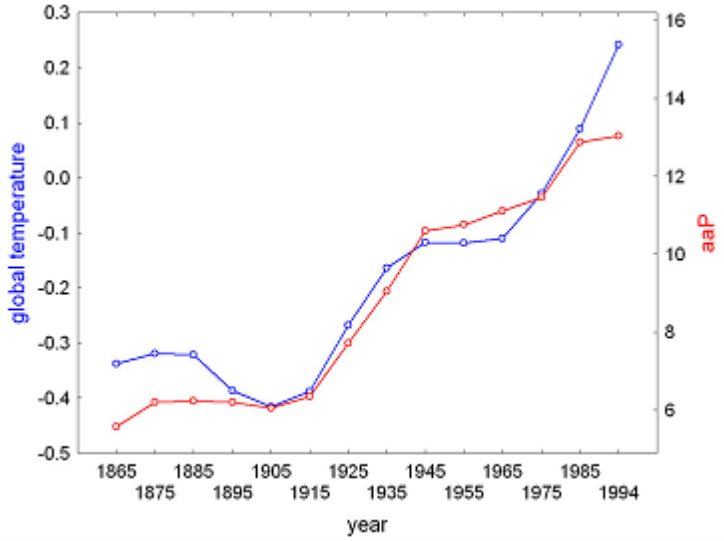
- Galactic Cosmic Rays - coming from outside the solar system, remnants of supernova stars
- Interact with atmospheric constituents to produce radionucleides
- The open solar flux modulates the cosmic rays flux and ⇒ the abundance of radionucleades

Reconstruction of the open flux back to 1700



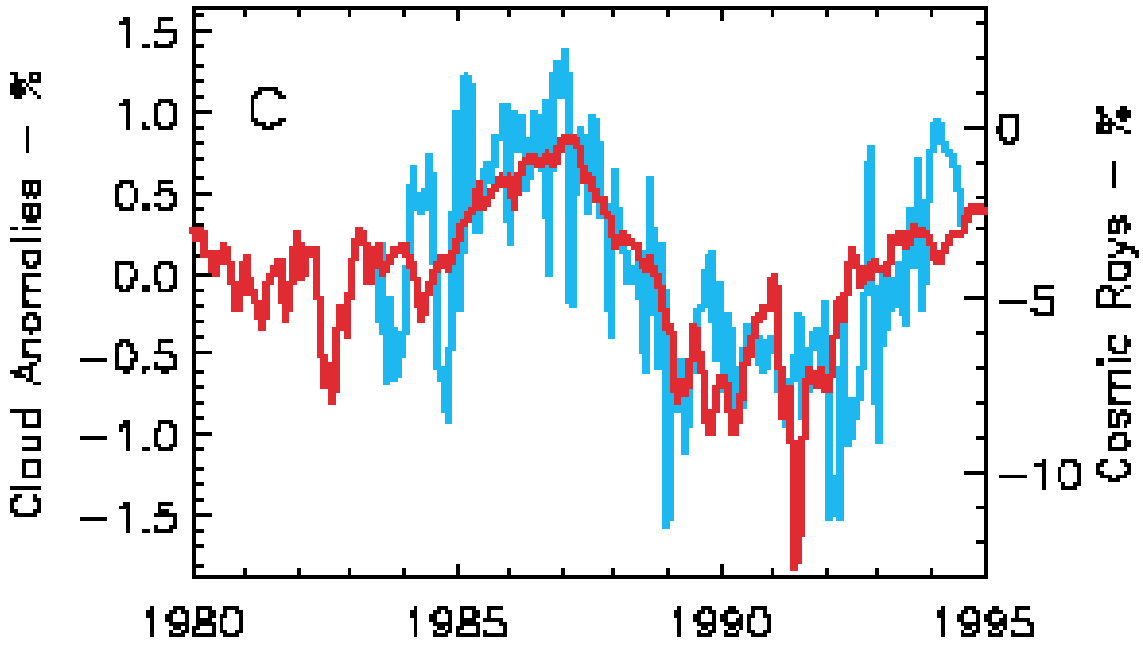
Correlation with global temperature





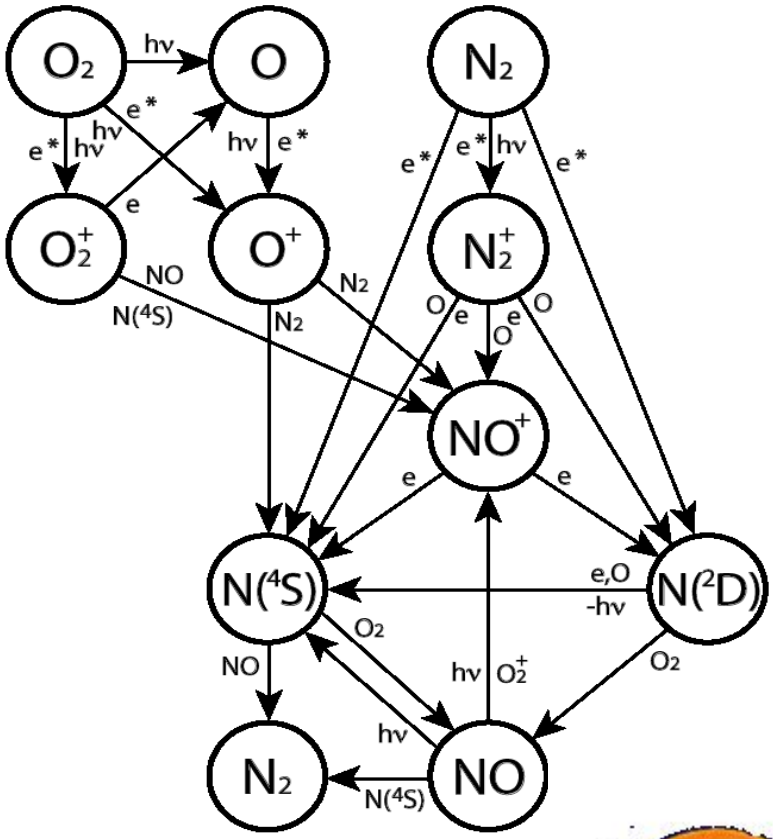
Geomagnetic activity caused mainly by **non-sunspot-related, or poloidal solar field-related** solar activity is better correlated to **global surface air temperature** than **sunspot number-related, or toroidal solar field-related** solar activity

Correlation between galactic cosmic rays and low clouds



Marsch and Svensmark, 2000

Possible mechanisms

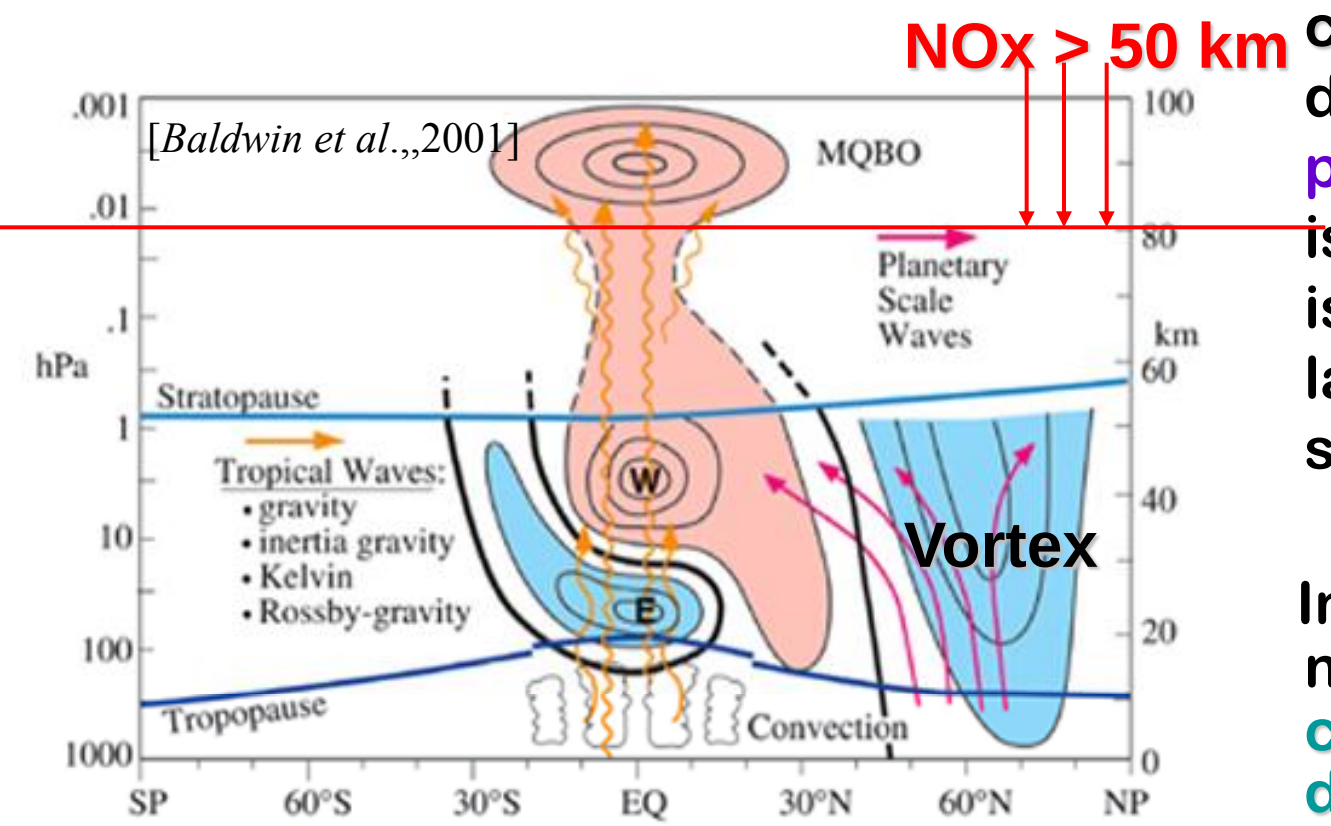


1) Effects of energetic particle precipitation on nitric oxide

- Produce NOx by ionizaton & dissociation
- Participates in the catalytic destruction of ozone.

Randell, ESSE, 2006

The Indirect EPP Effect on Ozone



Air from the upper atmosphere (which contains NOx) descends in the dark polar vortex where it is confined & isolated from other latitudes which are sunlit.

Increased odd nitrogen lifetime and catalytical destruction of ozone

Kozyra, ISSC 2006

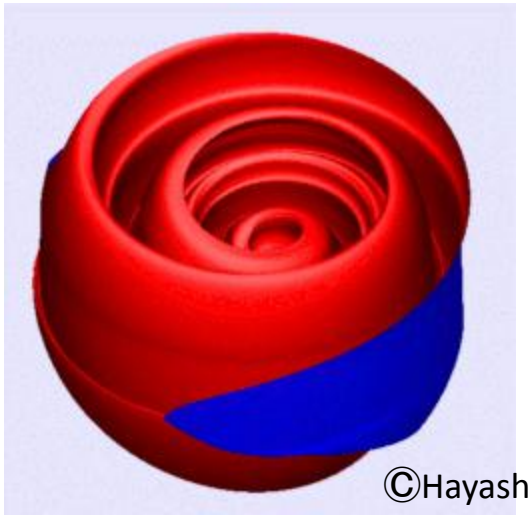
Possible mechanisms

2) Open flux modulation of galactic cosmic rays

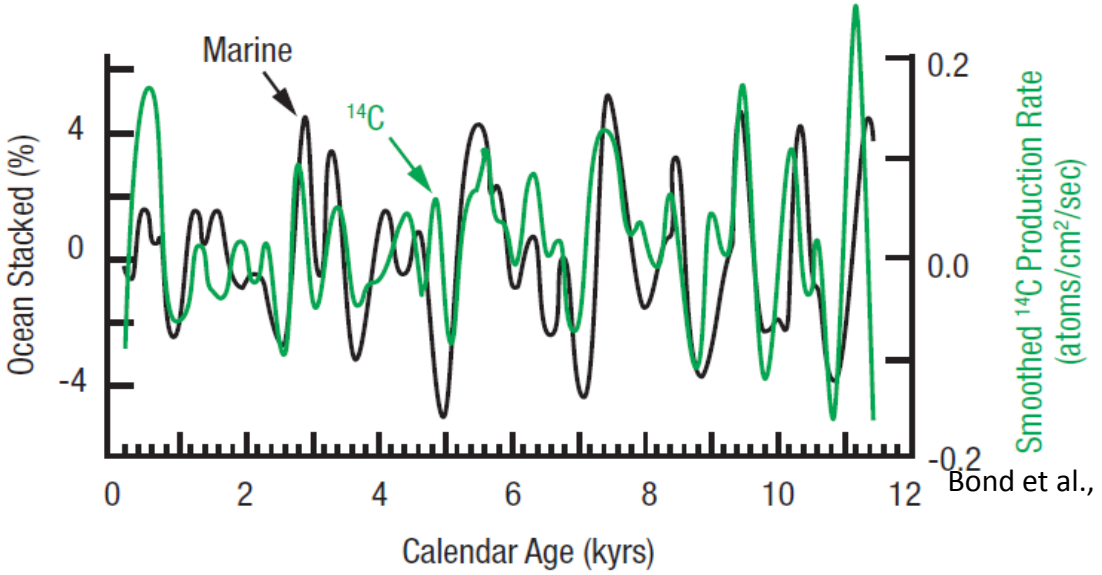
Effects of Galactic Cosmic Rays on Weather and Climate

- Evidences from the past:
  Solar forcing of climate
- How to identify the cosmic-ray effect
- Influence of 27-day solar rotations on clouds

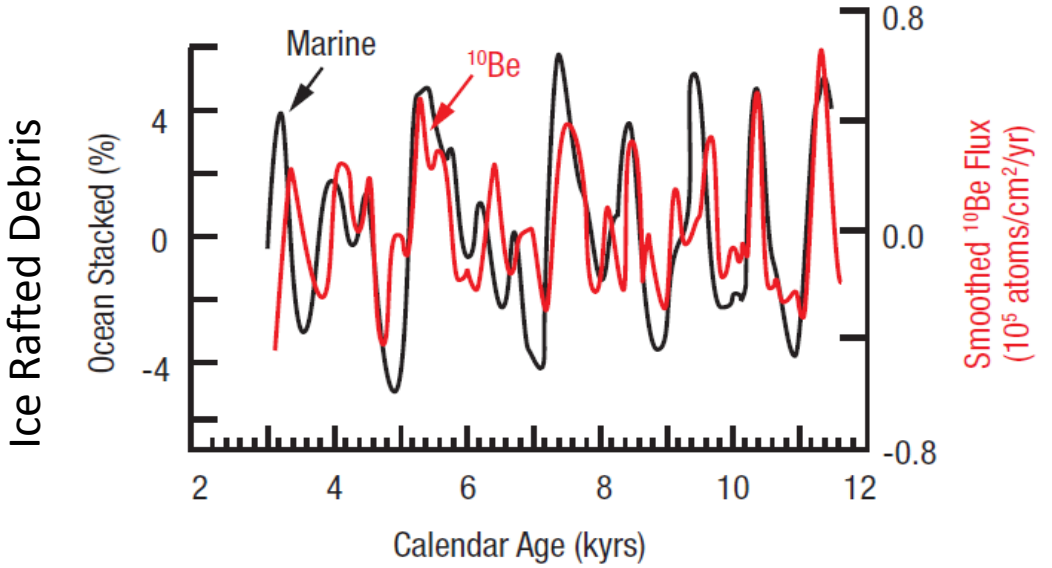
Heliosphere



Evidence from the past: Solar activity and climate variations

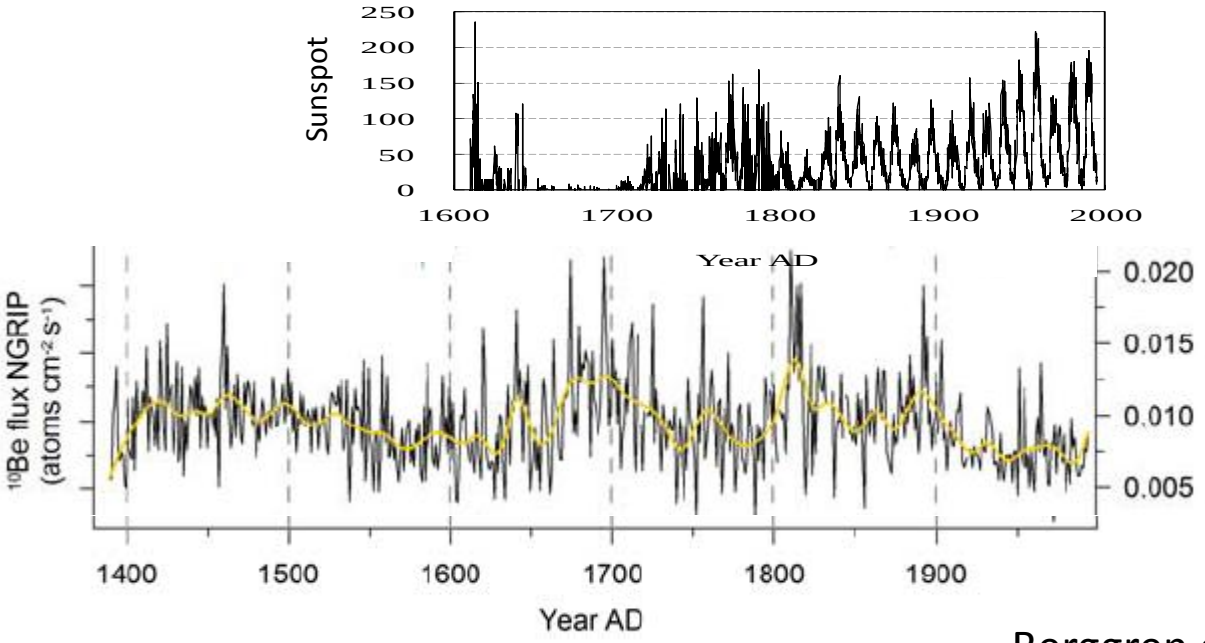


Bond et al., 2001



Bond et al., 2001

Characteristic 22-year variation in cosmic rays during the Maunder Minimum (1645-1715AD) revealed by beryllium-10 in Greenland ice core



Berggren et al., 2009

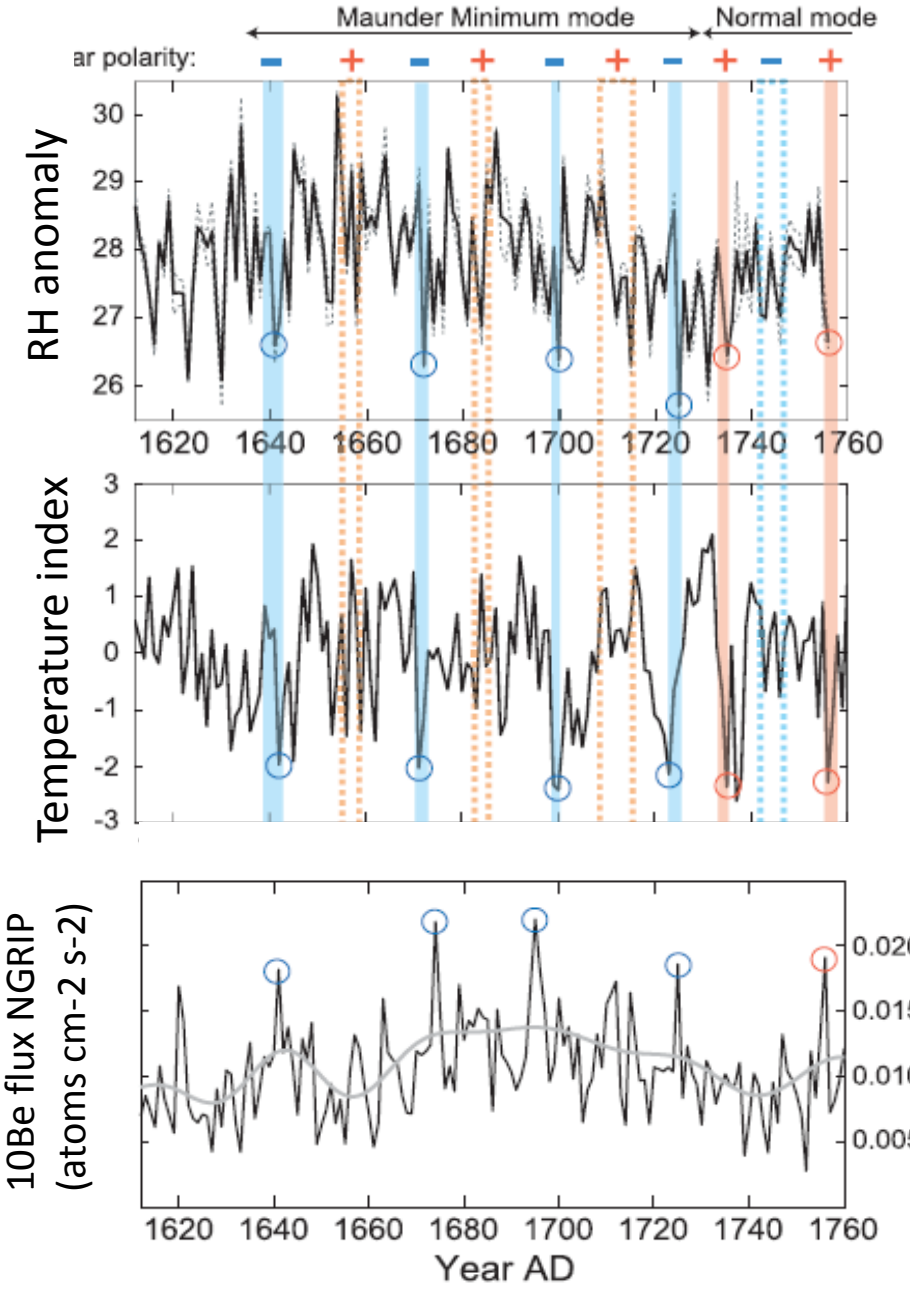
Spoerer Minimums

Maunder Minimum

Dalton Minimum

Climate response to cosmic-ray spikes during the Maunder Minimum

Yamaguchi, Miyahara et al., PNAS, 2010



Dry

Humidity in Japan around June

Humid

Warm

Greenland winter temperature

Cold

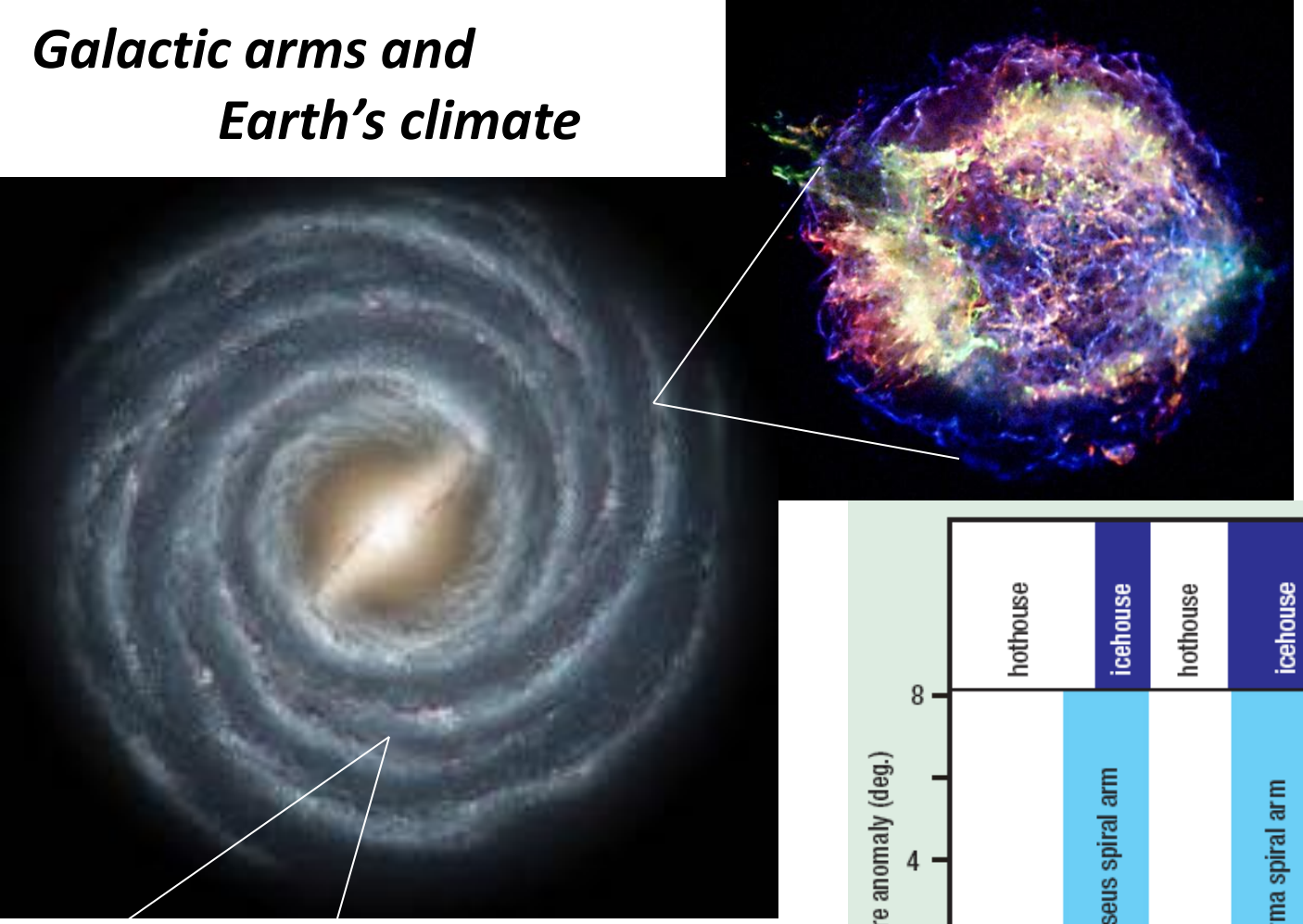
High

GCR flux
(Berggren et al., 2009)

Low

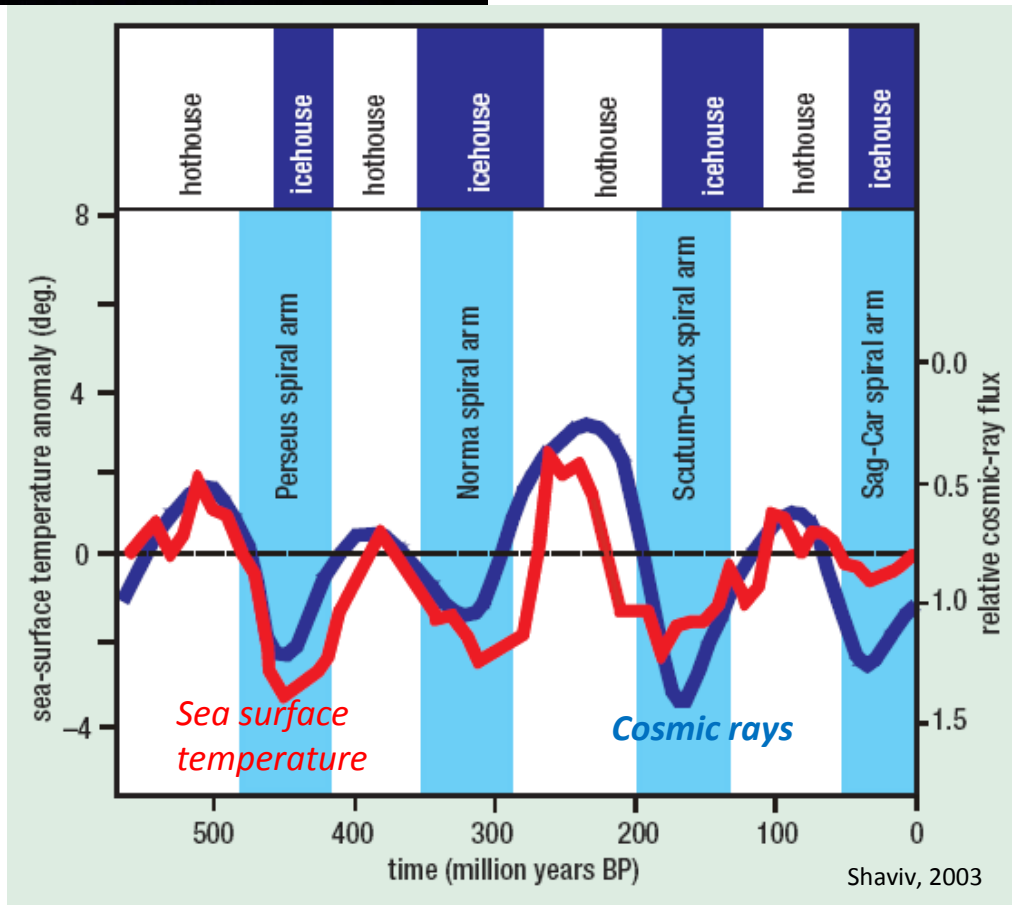
These spikes can be utilized to trace GCR effect on ***climate system***

Galactic arms and Earth's climate



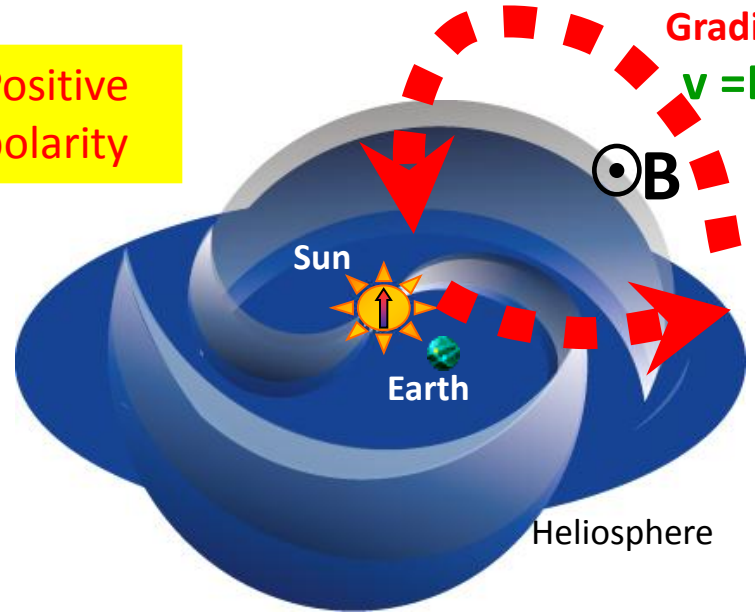
Supernova remnant accelerating cosmic rays

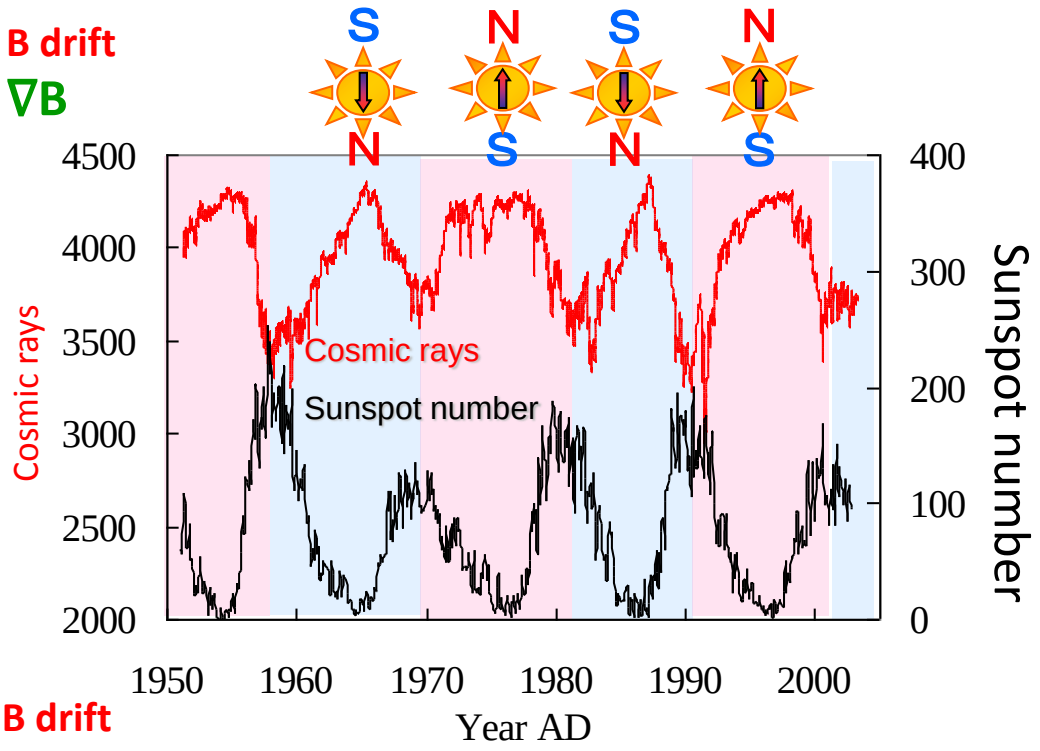
Colder climate when in the galactic arm



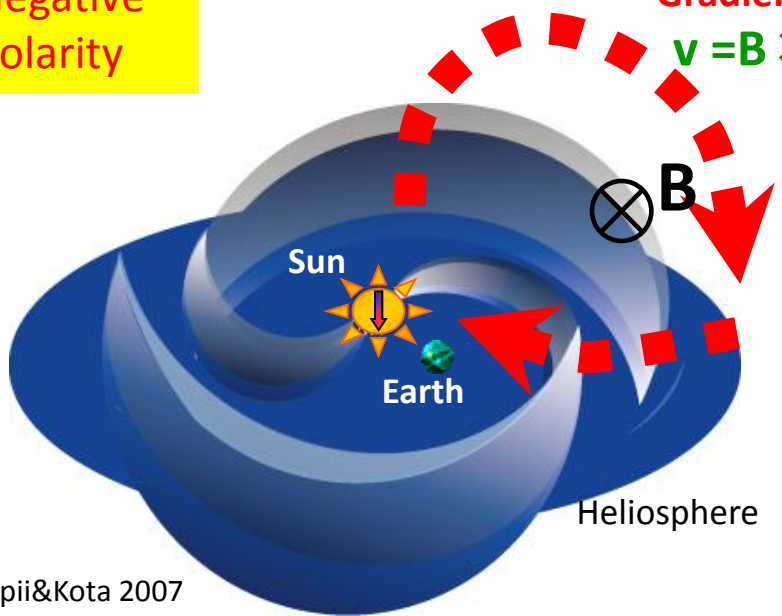
Cosmic ray variation & Solar magnetic polarity

Positive polarity

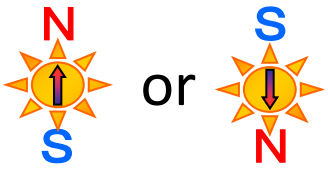




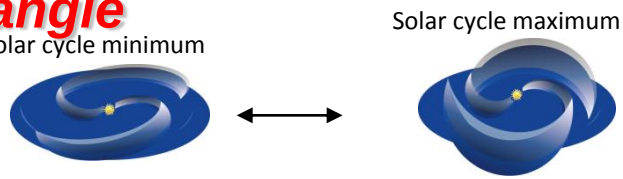
Negative polarity



1. Magnetic polarity

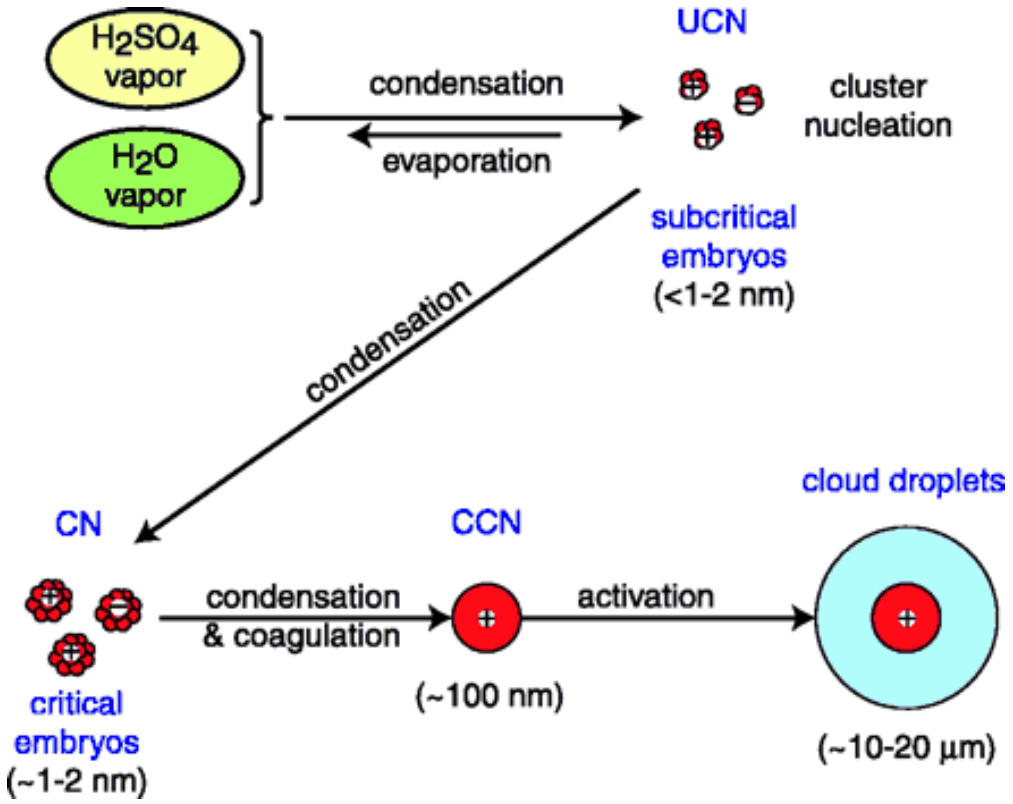


2. Tilt angle



Jokipii&Kota 2007

GCR ionization aids particle formation



Carslaw et al. (2002)

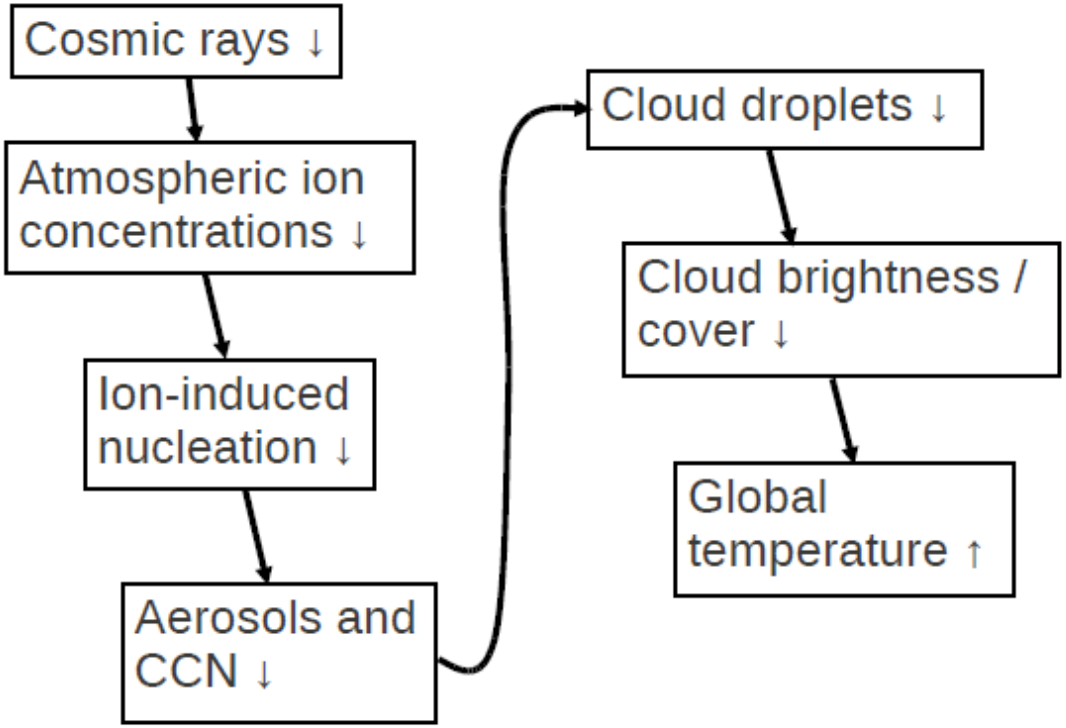


Fig. 1. The ion-aerosol clear-sky mechanism showing how cloud cover could be reduced and temperature could be increased from a decrease in cosmic rays.

Snow-Kropla et al, 2011

How can we quantitatively evaluate the relative role of the Sun and the anthropogenic greenhouse gases for global warming?

(How we should NOT do it)

Two approaches:

Modes simulations

- Know what factors affect climate and how
- Input them in climate simulation models
- Vary their amplitudes
- Compare the response

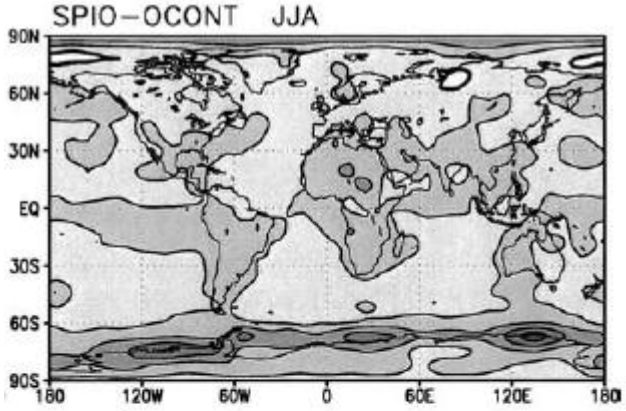
Statistics

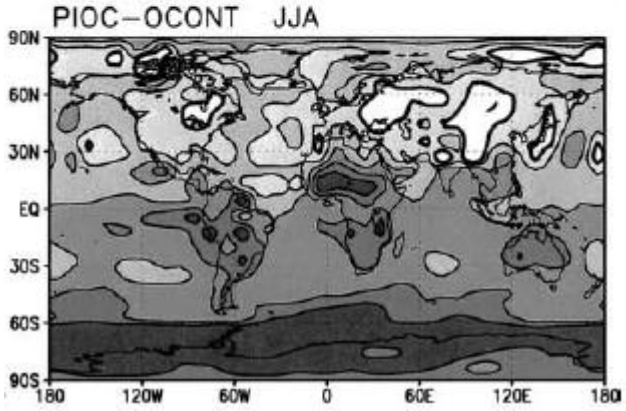
- Find out how Sun affected climate in the past
- Calculate for the present levels of solar activity
- Compare with the observed climate change

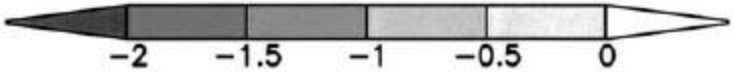
Example – simulation

difference present day - Maunder minimum

Rind et al. (2004)







Assume that:

- 2 factors affect climate solar irradiance and greenhouse gases
- We know how they affect it

- The same greenhouse gases, different solar irradiance

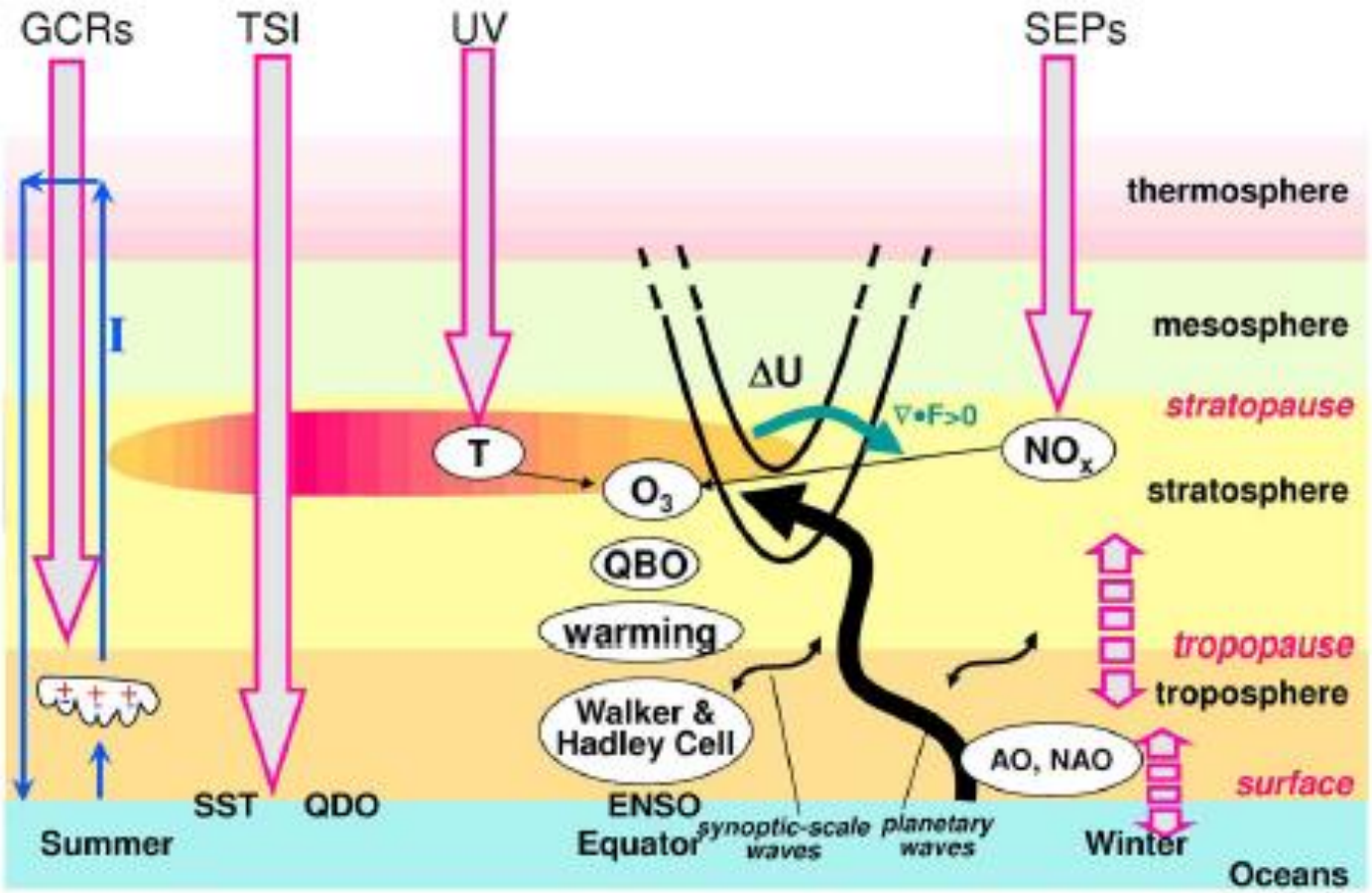
  -0.55° C

- The same solar irradiance, different greenhouse gases

  -1.11° C

⇒ The anthropogenic forcing is 2 times larger

Too many factors affect climate, and we don't yet know how

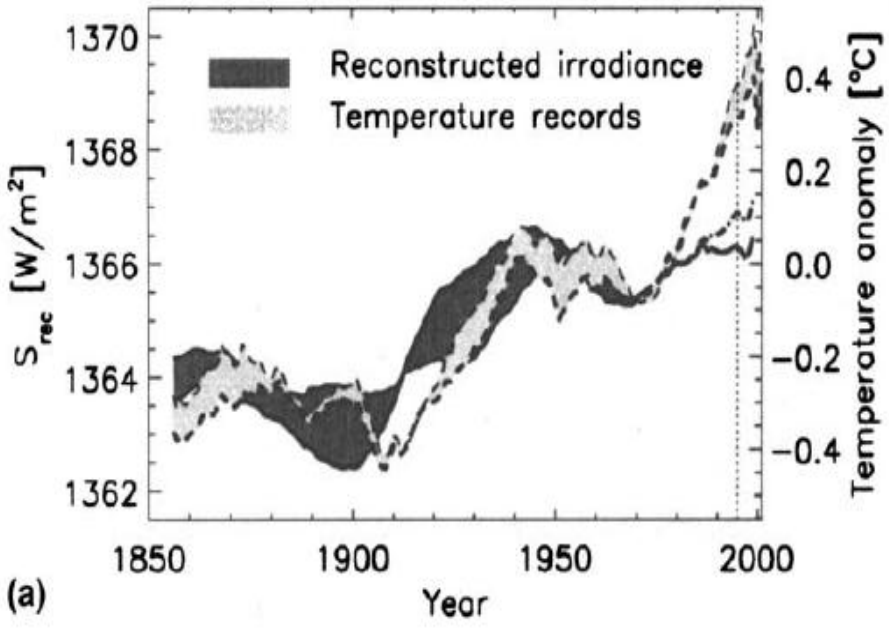


Example – statistics

Krivova and Solanki (2004)

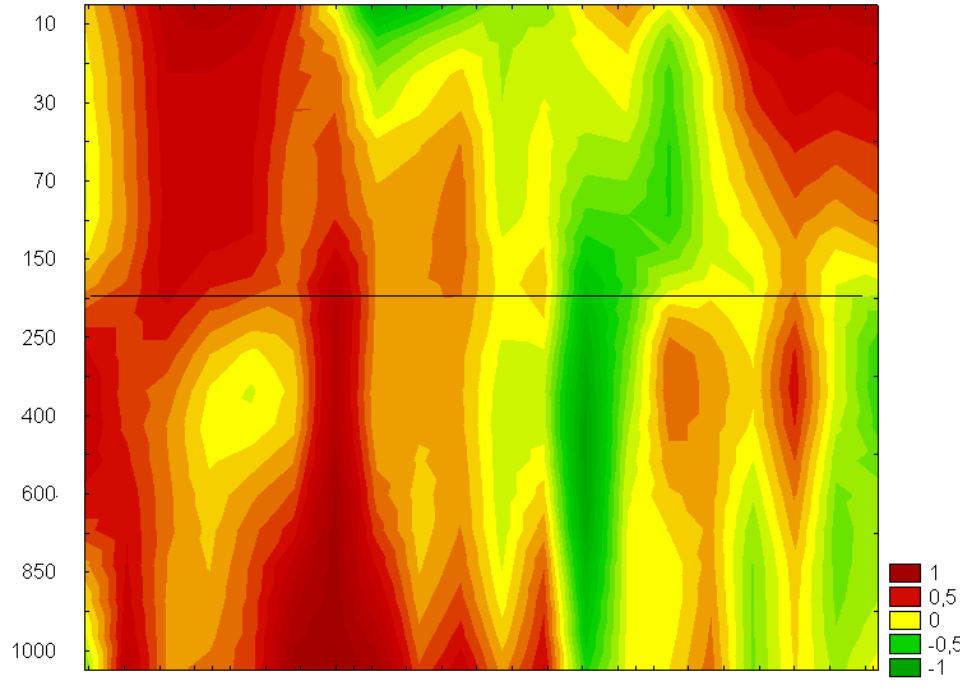
Assume that:

- **Sun (≡ solar irradiance) caused all climate change prior to 1970**
- **the interrelations between Sun and climate have not changed**

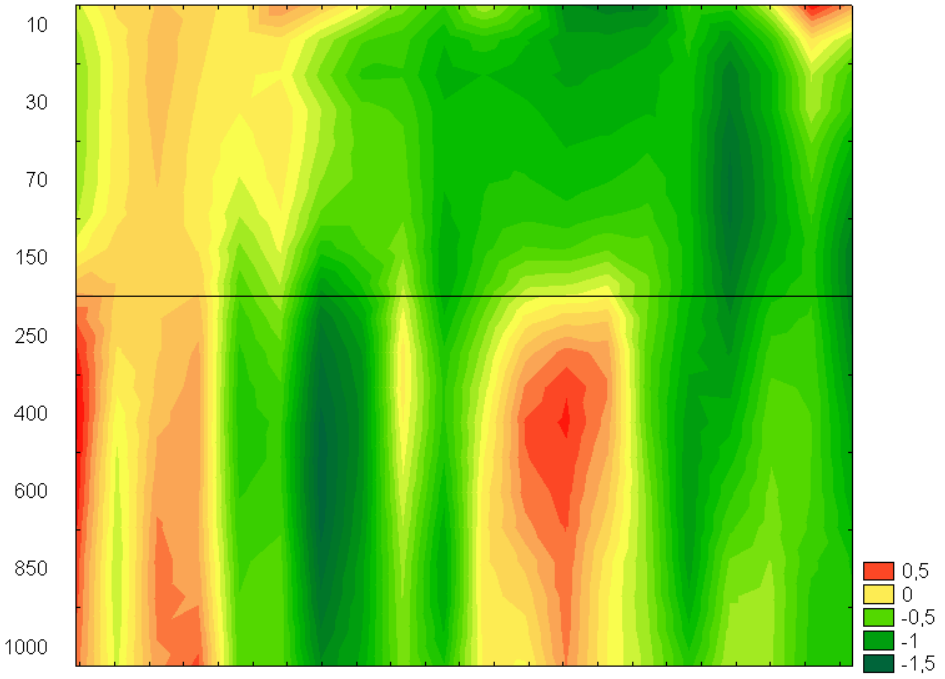


⇒ Sun cannot have been responsible for more than 30% of the recent rise in temperature

Different influence on climate
Example: NAM

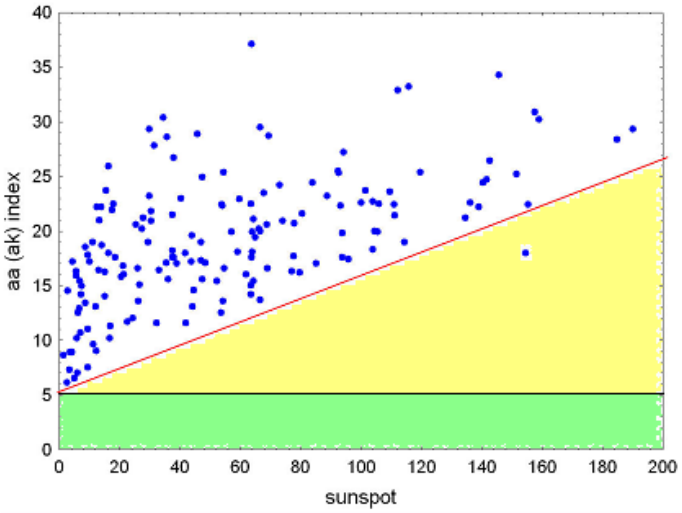


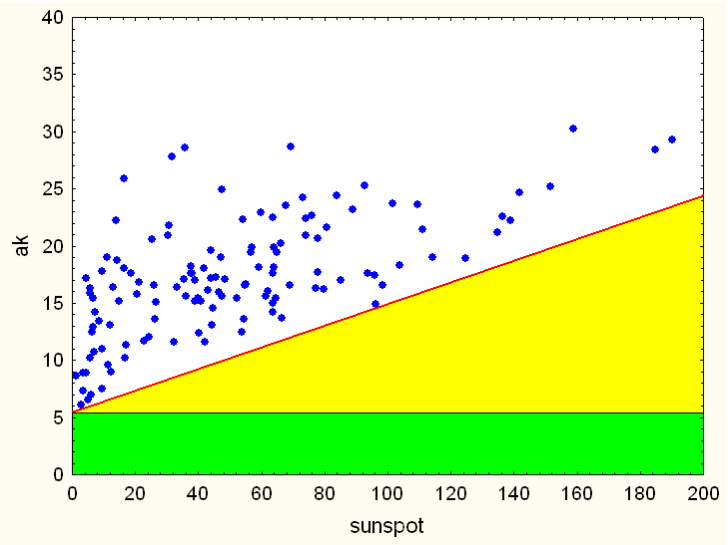
high irradiance, low geomagnetic activity

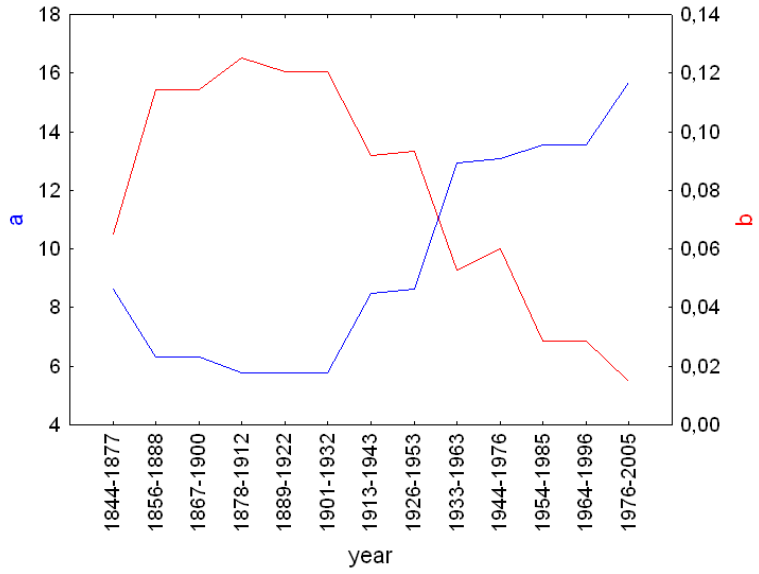


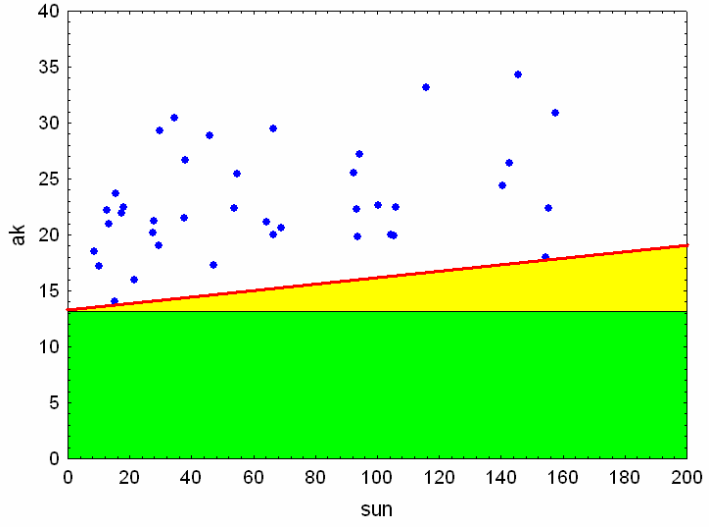
low irradiance, high geomagnetic activity

Long-term changes in the relative impact









conclusion

We are still far from evaluating the role of solar activity in climate change